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LOW PMD OPTICAL FIBER LINK, AND METHOD OF MAKING THE SAME

\* \* \* \* \*

DESCRIPTION

The present invention generally relates to the field of  
5 optical fibers and to manufacturing methods thereof. More  
particularly, the invention concerns an optical fiber link  
featuring a low Polarization Mode Dispersion (shortly, PMD),  
and a method of realizing it.

Optical signals transmitted through single-mode optical  
10 fibers comprise two orthogonal polarization modes (typically  
denoted Transverse Electric, or TE, and Transverse Magnetic,  
or TM). In case the fiber has a perfectly cylindrical core  
of uniform diameter, the two modes TE and TM propagate at a  
common velocity. However, in real optical fibers the  
15 cylindrical symmetry of the core may be disrupted due to  
shape defects or non-uniform stresses. As a result, a phase  
difference can accumulate between the two modes as they  
propagate, and the fiber is said to exhibit "birefringence".  
In particular, the birefringence introduced by shape and  
20 stress asymmetry is known as "intrinsic linear  
birefringence".

The structural and geometrical irregularities of the  
optical fiber that give rise to birefringence typically  
originate from the fiber preform itself, and are modified  
25 during the process of drawing the fiber. This process is  
usually carried out by means of an apparatus known as a  
"drawing tower", starting from a glass preform. In practice,  
after the preform has been placed in vertical position and  
heated to a temperature above the softening point within a  
30 suitable furnace, the molten material is drawn downwards at  
a controlled velocity in such a way as to produce a  
threadlike element that forms the optical fiber itself. In  
this process, asymmetrical stresses are typically applied to

the fiber.

In a birefringent fiber, the two components TE and TM of the fundamental optical mode, initially in phase with each other, return to be in phase again only after a certain propagation length, commonly known as the "beat length" ( $L_B$ ). In other words, the beat length is the period of repetition of a certain state of polarization (on the assumption that the fiber maintains a constant birefringence over this length). A further characteristic parameter of a birefringent fiber is the "correlation length" ( $L_F$ ), which is defined as the distance over which the autocorrelation function of the birefringence is  $1/e$  times its maximum value.

In the so-called "polarization-preserving" optical fibers, asymmetry is deliberately introduced into the fiber to generate birefringence. However, in ordinary (*i.e.*, non-polarization-preserving) fibers, birefringence is detrimental to the fiber performance.

In fact, when pulsed signals are transmitted into an optical fiber, birefringence is a cause of pulse spreading, since the two polarization components, TE and TM, travel at different group velocities (*i.e.* become dispersed). This phenomenon, known as Polarization Mode Dispersion (PMD), has been widely studied in recent years because of its importance in periodically amplified light guide systems.

Typically, the phenomenon of PMD leads to a limitation of the width of the signal transmission band and, consequently, a degradation of the performance of the optical fibers along which the aforesaid signals are transmitted. This phenomenon is therefore undesirable in systems of signal transmission along optical fibers, especially in those operating over long distances, in which it is necessary to minimize any form of attenuation or

dispersion of the signals to guarantee high performances in transmission and reception.

U.K. patent application GB-A-2101762 considers the effects on PMD of post-draw fiber twisting and observes that, although such twisting reduces the PMD resulting from intrinsic linear birefringence, it introduces torsional stresses that generate a substantial circular birefringence due to the photo-elastic effect. Twisting a drawn fiber thus reduces the bandwidth limitation due to one effect, whilst replacing it with another. The same patent application thus proposes to spin the preform during drawing, so that twisting can be effected whilst keeping the fiber material substantially unstressed. Spinning is performed at a relatively high rate, so that its spatial repetition frequency, or spin pitch, is small compared to the beat length due to intrinsic birefringence; as a result, an optical fiber can be produced wherein the contribution of birefringence due to form and stress asymmetries is greatly reduced. Such a fiber is termed "spun" fiber, to distinguish it from a (post-drawn) twisted fiber. Conveniently, the preform is spun at a substantially constant rate, but it could even reverse in direction, oscillating from a right-handed to a left-handed twist.

In the present description, the same distinction as above will be made between "spin" and "twist". More precisely, the terms "spin" and "twist" are herein used to identify two different types of torsion of the fiber: "spin" identifies a torsion that is frozen-in during drawing, being applied to a viscous portion of the fiber and kept as a structural modification of the fiber while cooling; differently, "twist" identifies an elastic torsion of the fiber, which is present when a torque is applied to a portion of fiber whose ends are constrained against

rotation. In other words, although both spin and twist alter the fiber in shape, so that parts previously in the same straight line are located in a spiral curve, a twisted fiber will rotate back to its original shape when its ends are released from the rotation constraint, while a spun fiber will keep this alteration as an intrinsic and permanent deformation. Due to spinning, the fiber undergoes a rotation of its polarization axes. As a result, when optical pulses are transmitted into the optical fiber, they propagate alternately on the slow and fast birefringence axes, thus compensating the relative delay and reducing the pulse spreading. This is equivalent to having a local effective refractive index for the optical pulses equal to the mean refractive index on the two axes, the average being taken over the pulse length along the fiber.

Theoretical studies have shown that the dominant process for the reduction of PMD in a spun fiber is the averaging of the local fiber anisotropy by the rapid procession of the axes of asymmetry along the fiber.

The United States patent US 4,504,300, relating to a technique for making an optical fiber having chiralic structure, addresses drawbacks related to preform rotation and proposes a new spinning technique, consisting in rotating the fiber instead of the preform. In particular, a device is disclosed comprising means disposed just below the preform for twisting the fiber during fiber drawing. The twisting means comprise a rotating hoop supporting three pulleys. The twisted fiber is coated by coating means, followed by cooling by fast-cooling means that facilitate freezing-in of the twist.

The United States patent US 5,418,881 proposes to arrange the device adapted to apply the torque to the fiber downstream of the coating station, so as to avoid damaging

the fiber surface. In particular, the torque is applied by alternately canting in clockwise and counterclockwise direction a fiber-guiding roll having a rotation axis which extends perpendicularly to the drawing axis of the fiber. In this way, in at least a portion of the fiber the spin impressed to the fiber is alternately clockwise and counterclockwise. The same patent states that applying a clockwise and a counterclockwise torque to the fiber substantially prevents introduction of an elastic twist to the fiber.

10       The United States patent application N. US2001/0020374 proposes a new device that overcomes some drawbacks of the canting-roll technique and allows both unidirectional and alternate spinning, but also states that alternate spinning is to be considered as preferable since it prevents the  
15       presence of residual torsions (*i.e.*, of a residual twist) on the fibers wound onto the collecting spool, thus making easier both the unwinding and wiring operations of the same.

      In the United States patent US 5,943,466, it is proposed to spin the fiber during drawing in accordance with  
20       spin functions which are not substantially constant (in the sense that they change substantially as a function of distance along the length of a fiber or as a function of time), not substantially sinusoidal, and have sufficient variability (*e.g.* sufficient harmonic content) to provide a  
25       substantial reduction in PMD for a plurality of beat lengths.

      The Applicant has found some other drawbacks of the alternate spinning technique, not previously highlighted. Alternate spinning may for example cause a relatively low  
30       mechanical efficiency of the spinning device, due to the continuous accelerations and decelerations. Moreover, with respect to a unidirectional spin, an alternate spin requires a relatively high peak profile amplitude to compensate those



positions of the profile where the rotation slows down to change direction and, therefore, to guarantee a sufficient average spin rate. Besides all this, the sites where the spin rate is zero are detrimental for the PMD, because there  
5 is an increase of the effective birefringence seen by the pulse, and so a higher contribution for PMD.

The paper by A. Galtarossa *et al.*, "PMD statistical properties of constantly-spun fibers", ECOC-IOOC 2003 Proceedings, Vol. 4, Th. 1.7.4, and the paper by A.  
10 Galtarossa *et al.* "Polarization mode dispersion properties of constantly spun randomly birefringent fibers", Optics Letters, vol 28 No.18, September 2003, pp. 1639-1641 report the PMD induced delay (*i.e.* the mode delay - in ps - induced by PMD or, equivalently, the mean fiber Differential Group  
15 Delay, or "DGD") of unidirectionally-spun fibers. It can be shown that, while in an unspun fiber or an alternately spun fiber the PMD induced delay increases proportionally to the square root of the fiber length, in a unidirectionally-spun fiber the PMD induced delay has a higher increase rate, and  
20 only asymptotically increases proportionally to the square root of length. In particular, the PMD induced delay in a unidirectionally-spun fiber asymptotically increases at the same rate as the PMD induced delay of an unspun fiber having the same beat length  $L_B$  and the same correlation length  $L_F$ .  
25 Advantageously, a PMD coefficient, hereinafter indicated with  $PMD_c$ , defined as the mean fiber DGD divided by the square root of length, is introduced. For unspun or alternately spun fibers, this parameter is independent from the fiber length.

30 In greater detail, reference is made to **Figure 1**, wherein a theoretical diagram of the average of the squared DGD  $\langle \Delta\tau^2 \rangle$  (in ordinate, unit  $ps^2$ ) as a function of the propagation distance (in abscissa, unit km) is shown for an

unspun fiber (curve (a)) with a typical (constant)  $PMD_c$  (e.g.,  $0.1 \text{ ps/km}^{1/2}$ ), an alternately spun fiber (curve (b)) with a typical (constant)  $PMD_c$  (e.g.,  $0.04 \text{ ps/km}^{1/2}$ ) and a unidirectionally spun fiber (curve (c)) with the same beat  
5 length  $L_B$  and the same correlation length  $L_F$  as the unspun fiber. From the diagram, it can be appreciated that the slope of curve (c) (i.e. the increase rate of  $\langle \Delta \tau^2 \rangle$ ) is not constant, but increases with the propagation distance up to a constant value corresponding to the slope of curve (a).  
10 The length over which the slope changes can be denoted as a transient length. Since the  $PMD_c$  is proportional to the square root of  $\langle \Delta \tau^2 \rangle$  divided by the square root of the fiber length, it is expected that such a coefficient increases with the propagation distance (i.e. with the fiber length),  
15 differently from the  $PMD_c$  of unspun and alternately spun fibers, which is constant. In particular, for the unidirectionally spun fiber, the increase of the  $PMD_c$  will be more rapid in the initial transient, before the increase rate of the  $PMD_c$  becomes similar to that of the unspun  
20 fiber; after the transitory, the  $PMD_c$  increases very slowly reaching asymptotically the  $PMD_c$  of the unspun fiber. As already predicted in the article by Galtarossa et al., "Optimized Spinning Design for Low PMD Fibers: An Analytical Approach" Journal of Lightwave technology vol. 19 no.10 Oct.  
25 2001 pp. 1502-1512, the initial  $PMD_c$  increase is the one predicted in the deterministic regime.

In the above-cited articles by Galtarossa, it is also described that the magnitude of the spin period changes the length of the above-mentioned transient regime, and that a  
30 transient characteristic length  $L_T$  can be defined for unidirectionally spun fibers (curve (c) in **Figure 1**):

$$L_T = L_F \left( 1 + \frac{4L_B^2}{P^2} \right)$$

where  $p$  is the spinning period,  $L_F$  the correlation length and  $L_B$  the beat length. The transient characteristic length  $L_T$  is equal to the intercept of the linear asymptotic behavior of curve (c) with the abscissa axis. The  
5 propagation distance (or length of fiber span) required to approach the regime PMD behavior of the unspun fiber is estimated to be of some transient characteristic lengths.

Assuming that the parameters appearing in the above formula fall within the typical ranges:  $L_F = 1 \div 20$  m,  $L_B = 5$   
10  $\div 15$  m, and  $p = 0.1 \div 1$  m, the transient characteristic length  $L_T$  may vary between 0.1 and 1,800 km, covering four orders of magnitude. If the transient characteristic length  $L_T$  is much greater than the link length, the PMD<sub>c</sub> increase remains moderate. On the contrary, when the transient  
15 characteristic length  $L_T$  is comparable to or smaller than the link length, the PMD<sub>c</sub> increase over the link becomes significant and can be detrimental to signal transmission.

Thus, unidirectionally spun fibers with short transient characteristic lengths suffer from a growth of the PMD<sub>c</sub> with  
20 the fiber length, which cancel the advantage of using a spun fiber.

Another prediction made in the cited paper by A. Galtarossa published in Optics Letter is that the DGD statistical distribution for short enough unidirectionally  
25 spun fibers may deviate from the typical Maxwell distribution exhibited by both unspun and alternately spun fibers.

In view of the state of the art outlined in the foregoing, it appears that an optimum solution to the  
30 problem of PMD in fibers does not exist: unspun fibers have in fact a PMD which, for several applications, is too high; on the other hand, alternately spun fibers exhibit the series of problems previously mentioned. From the above

theoretical considerations it also comes out that unidirectionally spun fiber may be preferable with respect to unspun fibers only for relatively short fiber lengths, because they experience a growth of their PMD<sub>c</sub> as the length  
5 increases, which becomes asymptotically equal to the one of unspun fibers.

Thus, it has been an object of the present invention to devise a solution to these problems.

In particular, it has been an object of the present  
10 invention to provide an optical fiber link, and a method of realizing it, featuring a significant limitation of the PMD<sub>c</sub> increase with fiber length.

With these objects in mind, the Applicant has found that the increase in the PMD<sub>c</sub> exhibited by unidirectionally  
15 spun fibers can be completely eliminated or substantially reduced if an optical fiber link is made of unidirectionally spun fiber spans, of appropriate lengths, with opposite helicity, spliced one to the other to form the optical fiber. With "helicity", it is here intended the fiber spin  
20 direction, which can be either right-handed or left-handed (i.e. clockwise or counter clockwise).

Therefore, an optical fiber link according to the present invention includes at least a first and a second optical fiber spans unidirectionally-spun in opposite  
25 directions and joined to each other. Preferably, the optical fiber link comprises a first type of fibers unidirectionally-spun in a first direction, and a second type of fibers unidirectionally-spun in the opposite direction, the fibers of the first type being alternated to  
30 the fibers of the second type, i.e. fiber spans of opposite helicity are alternated to each other.

According to an aspect of the present invention, an optical fiber link is provided for, as set forth in appended

independent optical fiber link claim 1.

In brief, the optical fiber link comprises a plurality of optical fiber spans, joined one to the other, said plurality of optical fiber spans including at least one  
5 first unidirectionally-spun optical fiber span and at least one second unidirectionally-spun optical fiber span having mutually opposite spinning directions.

For the purposes of the present invention, the terms "spin", "spinning" and "spun" all relate to a torsion that  
10 is frozen-in during drawing, being applied to a viscous portion of the fiber and kept as a structural modification of the fiber while cooling. In other words, a spun fiber will keep this alteration as an intrinsic and permanent deformation.

Also, for the purposes of the present invention, with "unidirectional spin" it is intended a spin that occurs on a same direction apart from possible local inversions, for example due to fiber slippage in the spinning device or in the traction device.

Preferably, the unidirectional spin here considered is constant, but it may also derive from the superposition of a constant spin function and a variable spin function, the variable spin function having preferably small amplitude and long period.

Preferably, the first unidirectionally-spun optical fiber span and the second unidirectionally-spun optical fiber span are joined to each other.

In a preferred embodiment of the present invention, the plurality of optical fiber spans includes a plurality of  
30 first optical fiber spans, and a plurality of second optical fiber spans, the first optical fiber spans and the second optical fiber spans being spans of unidirectionally spun optical fibers having mutually opposite spinning directions.

The first optical fiber spans and the second optical fiber spans are alternated to each other in the optical fiber link.

5 The first unidirectionally-spun optical fiber span and the second unidirectionally-spun optical fiber span may have substantially a same span length.

Defined a spinning period  $p$ , a correlation length  $L_F$  and a beat length  $L_B$  for the fiber, the length of the first unidirectionally-spun optical fiber span and/or of the  
10 second unidirectionally-spun optical fiber span is preferably lower than 10 times the transient characteristic length  $L_T$  defined as

$$L_T = L_F \left( 1 + \frac{4L_B^2}{p^2} \right).$$

More preferably, said span length is lower than 5 times  
15 the transient characteristic length  $L_T$ .

In an embodiment of the present invention, said span length is equal to or lower than approximately 3 Km, preferably equal to or lower than approximately 1 Km.

In particular, the first unidirectionally-spun optical  
20 fiber span and the second unidirectionally-spun optical fiber span may have substantially a same spin rate.

Preferably, the number of first optical fiber spans and second optical fiber spans is odd.

According to another aspect of the present invention,  
25 an optical cable line as set forth in appended claim 10 is provided.

Summarizing, the optical cable line includes a plurality of optical cable trunks joined to each other. Said plurality of optical cable trunks comprises at least a first  
30 optical cable trunk and a second optical cable trunk, the first optical cable trunk including a first optical fiber span unidirectionally-spun in a first direction, and the

second optical cable trunk including a second optical fiber span unidirectionally-spun in a second direction opposite to the first direction, the first and the second optical fiber spans being optically linked to each other.

5 In particular, the first and the second optical fiber spans are joined to each other.

The first and the second optical fiber spans may have substantially a same span length.

10 Preferably, the span length of the first and/or of the second optical fiber span is lower than 10 times the transient characteristic length  $L_T$  defined above, more preferably lower than 5 times the transient characteristic length  $L_T$ . In particular, the fiber span is preferably equal to or lower than approximately 3 Km, more preferably equal  
15 to or lower than approximately 1 Km.

In particular, the first and the second optical fiber spans may have substantially a same spin rate.

According to an embodiment of the present invention, the plurality of optical cable trunks include a plurality of  
20 first optical fiber spans, and a plurality of second optical fiber spans joined to each other to form an optical fiber link, the first optical fiber spans and the second optical fiber spans being unidirectionally-spun optical fibers having mutually opposite spin directions, and the first  
25 optical fiber spans and the second optical fiber spans being alternated to each other in the optical fiber link.

In particular, in an embodiment of the present invention at least one optical cable trunk of said plurality of optical cable trunks has an optical core including a  
30 plurality of unidirectionally-spun optical fiber spans having a same spin direction.

In another embodiment of the invention, at least one optical cable trunk of said plurality of optical cable

trunks has an optical core including at least two unidirectionally-spun optical fiber spans having opposite spin directions.

5 Preferably, the total number of optical cable trunks is odd.

According to still another aspect of the present invention, a method of realizing an optical fiber link as set forth in appended independent method claim 21 is provided.

10 The method comprises:

providing at least a first span of optical fiber, unidirectionally-spun in a first direction;

providing at least a second span of optical fiber, unidirectionally-spun in a second direction opposite to the  
15 first direction; and

joining the first span and the second span together at a respective end thereof.

According to a further aspect of the present invention, a method of producing an optical cable as set forth in  
20 appended claim 22 is provided.

The method comprises providing a plurality of optical fibers to a cable manufacturing line, wherein said plurality of optical fibers comprises at least a first optical fiber being unidirectionally-spun in a first direction, and at  
25 least a second optical fiber being unidirectionally-spun in a second direction opposite to the first direction.

According to a still further aspect of the present invention, a method of realizing an optical cable line as set forth in appended claim 23 is provided.

30 The method comprises forming a plurality of optical cable trunks, each one including at least one optical fiber span, and joining the optical cable trunks one to another.

The step of forming a plurality of optical cable trunks



comprises forming at least one first trunk including a first optical fiber span unidirectionally-spun in a first direction, and forming at least one second trunk including a second optical fiber span unidirectionally-spun in a second direction opposite to the first direction; said joining the optical cable trunks one to another includes optically linking the first optical fiber span to said second optical fiber span.

These and other features and advantages of the present invention will be made apparent by the following detailed description of an embodiment thereof, provided merely by way of non-limitative example, description that will be conducted making reference to the attached drawings, wherein:

**Figure 1** is a diagram showing the predicted variation of the average of the squared Differential Group Delay (DGD) (in ordinate) with the propagation distance (in abscissa) for: an unspun fiber (curve (a)), an alternately spun fiber (curve (b)) and a unidirectionally spun fiber (curve (c)) with the same beat length  $L_B$  and the same correlation length  $L_F$  as the unspun fiber;

**Figure 2** schematically shows a portion of an optical fiber link according to an embodiment of the present invention, comprising alternated, unidirectionally spun fiber spans having mutually opposite helicity;

**Figures 3A** and **3B** show diagrams of the predicted variation of the PMD<sub>c</sub> (in ordinate, unit ps/km<sup>1/2</sup>) with the propagation distance (in abscissa, unit km) for the fiber of **Figure 2** for various lengths of the alternated fiber spans, and for two different values of the fiber transition characteristic length;

**Figure 4A** shows in transverse section an optical cable containing optical fibers in accordance to an embodiment of

the present invention;

**Figure 4B** schematically shows in lateral view a portion of an optical cable line in accordance with the present invention;

5       **Figure 5** is a diagram showing the predicted variation with the propagation length (in abscissa, unit km) of the ratio between the average of the squared DGD values to the square of the averaged DGD values (in ordinate) for a fiber with the same parameters of **Figure 3A**, with alternated spans  
10       length of 5 km;

**Figures 6A to 6F** are diagrams showing the statistical distribution of the DGD values for the same fiber of **Figure 5** at propagation distances indicated in **Figure 5** with the letters a) to f) respectively;

15       **Figure 7** shows a drawing tower adapted to drawing unidirectionally spun fibers;

**Figure 8** illustrates a spinning device suitable to be used in the drawing tower of **Figure 7**;

20       **Figure 9** shows a twist apparatus suitable to be used in the drawing tower of **Figure 7**;

**Figure 10** illustrates a re-spooling apparatus;

**Figure 11** shows a twist apparatus to be used in the drawing tower of **Figure 7**, in alternative to the apparatus of **Figure 9**; and

25       **Figures 12 and 13A to 13D** are diagrams showing the results of experiments conducted by the Applicant.

With reference to the drawings, in **Figure 2** a portion of an optical fiber link according to an embodiment of the present invention is shown very schematically.

30       By optical fiber link there is intended an optical fiber made up of two or more optical fiber spans, joined to each other.

The optical fiber link, indicated globally as **300**, is

for example of the type used in optical fiber cables for optical communication systems.

The optical fiber link 300 (the portion of which shown in **Figure 2** being for example an intermediate portion along the overall length of the optical fiber link) comprises a plurality of optical fiber segments or spans ..., 305<sub>(k-1)</sub>, 305<sub>k</sub>, 305<sub>(k+1)</sub>, 305<sub>(k+2)</sub>, 305<sub>(k+3)</sub>, 305<sub>(k+4)</sub>, 305<sub>(k+5)</sub>, 305<sub>(k+6)</sub>, ..., of shorter length, joined one to another at respective free ends to form the optical fiber link 300; in jargon, the operation of joining of two optical fiber segments together is referred to as "splicing"; in the drawing, the points where two generic optical fiber spans ..., 305<sub>(k-1)</sub>, 305<sub>k</sub>, 305<sub>(k+1)</sub>, 305<sub>(k+2)</sub>, 305<sub>(k+3)</sub>, 305<sub>(k+4)</sub>, 305<sub>(k+5)</sub>, 305<sub>(k+6)</sub>, ..., are spliced together are schematically indicated by 310.

According to an embodiment of the present invention, the optical fiber spans ..., 305<sub>(k-1)</sub>, 305<sub>k</sub>, 305<sub>(k+1)</sub>, 305<sub>(k+2)</sub>, 305<sub>(k+3)</sub>, 305<sub>(k+4)</sub>, 305<sub>(k+5)</sub>, 305<sub>(k+6)</sub>, ..., are segments or spans of unidirectionally spun optical fibers. In particular, spans of unidirectionally spun optical fibers with mutually opposite spinning helicity (right-hand, or  $\sigma_+$ , helicity and left-hand, or  $\sigma_-$ , helicity) are exploited to form the optical fiber link 300, and the unidirectionally spun fibers spans with right-hand, or  $\sigma_+$ , spinning helicity are alternated to the unidirectionally spun fibers spans with left-hand, or  $\sigma_-$ , spinning helicity, as schematically depicted in the drawing. Preferably, the unidirectional spin of the different fiber spans is constant in module.

Due to the fact that splicing together fibers with opposite helicity interrupts the transients of the PMD<sub>c</sub> of a unidirectionally-spun fiber towards the unspun fiber value, the growth of the PMD<sub>c</sub> of the optical fiber link 300 with the fiber link length, discussed in the introductory part of the present description, may be substantially reduced by the

above-described provision in the fiber link 300 of both type of fiber spans.

In principle, the lengths of the individual fiber spans ..., 305<sub>(k-1)</sub>, 305<sub>k</sub>, 305<sub>(k+1)</sub>, 305<sub>(k+2)</sub>, 305<sub>(k+3)</sub>, 305<sub>(k+4)</sub>, 305<sub>(k+5)</sub>, 5 305<sub>(k+6)</sub>, ..., might be whatsoever, but, as will be shown in the following, a careful choice of such lengths allows substantially reducing, or even eliminating, the effect of growth of the PMD<sub>c</sub> with the fiber length (thereby, after a certain length, a practically constant PMD<sub>c</sub> is achieved, 10 lower than the one of the single-helicity, unidirectionally-spun fiber).

In particular, if the spin rates of the unidirectionally spun optical fibers with  $\sigma_+$  helicity have substantially the same magnitude (modulus) as the spin rates 15 of the unidirectionally spun optical fibers with  $\sigma_-$  helicity, the best results in terms of suppression of the PMD<sub>c</sub> growth with the fiber link length are achieved by alternating, along the fiber link 300,  $\sigma_+$  and  $\sigma_-$  optical fiber spans of substantially same lengths. However, if the 20 spin rates of the unidirectionally spun optical fibers with  $\sigma_+$  helicity have a different magnitude (modulus) from the spin rates of the unidirectionally spun optical fibers with  $\sigma_-$  helicity, the lengths of the different  $\sigma_+$  and  $\sigma_-$  optical fiber spans should depend on the respective spin rate 25 absolute values.

Reference is now made to **Figures 3A** and **3B**, which are diagrams of the predicted variation of the PMD<sub>c</sub> (in ordinate, unit ps/km<sup>1/2</sup>) with the propagation distance (in abscissa, unit km) for the fiber link 300 for various 30 lengths of the alternated fiber spans ..., 305<sub>(k-1)</sub>, 305<sub>k</sub>, 305<sub>(k+1)</sub>, 305<sub>(k+2)</sub>, 305<sub>(k+3)</sub>, 305<sub>(k+4)</sub>, 305<sub>(k+5)</sub>, 305<sub>(k+6)</sub>, ..., that make up the fiber link 300, and for two different values of the fiber transient characteristic length  $L_T$ . The curves

have been derived in accordance with the teaching of Galtarossa *et al.*, "Polarization mode dispersion properties of constantly spun randomly birefringent fibers", Optics Letters, vol 28 No.18, September 2003, pp. 1639-1641, relative to fibers with a single spin direction.

In particular, the diagram of **Figure 3A** relates to an optical fiber link **300** made up of alternated unidirectionally spun fiber spans of opposite helicity having a spinning period  $p = 0.25$  m, a beat length  $L_B = 7$  m, a correlation length  $L_F = 10$  m, and consequently a transient characteristic length  $L_T = 32$  km. The diagram of **Figure 3B** relates instead to a similar optical fiber link **300**, but having a spinning period  $p = 0.5$  m, and thus featuring a transient characteristic length  $L_T = 8$  km. In both cases, the evolution of the  $PMD_c$  with the propagation distance for alternated fiber spans ...,  $305_{(k-1)}$ ,  $305_k$ ,  $305_{(k+1)}$ ,  $305_{(k+2)}$ ,  $305_{(k+3)}$ ,  $305_{(k+4)}$ ,  $305_{(k+5)}$ ,  $305_{(k+6)}$ , ..., of length  $L_C$  equal to 5 km, 10 km, 20 km, 40 km and for an infinite span length (*i.e.* for a single helicity fiber) is shown.

It can be appreciated that, in both cases, when alternating optical fiber spans unidirectionally-spun with opposite helicity, the  $PMD_c$  after a transient attains a substantially constant value which is lower than that of the single-helicity unidirectionally spun fiber, and hence of the unspun fiber with the same beat length  $L_B$  and correlation length  $L_F$ . So, the typical behavior of the single-helicity, unidirectionally-spun fiber is substantially transformed in a behavior similar to that of an alternately spun fiber.

Comparing the two diagrams, it can also be appreciated that the smaller the value of the transient characteristic length  $L_T$ , the smaller the span length  $L_C$  necessary to achieve a same value of the  $PMD_c$ . It can be appreciated by

those skilled in the art that an optimum  $L_c$  value can always be evaluated from the link length, the maximum allowed number of spans, and the transient characteristic length.

From the two diagrams of **Figures 3A** and **3B** it can also  
5 be noted that, for a value of the beat length  $L_B = 7$  m and a value of the fiber correlation length  $L_F = 10$  m, a span length  $L_c$  substantially equal to the transient characteristic length  $L_T$  gives a  $\text{PMD}_c$  of about  $0.04 \text{ ps/km}^{1/2}$ , that is a value comparable to the one of the commercially  
10 available, alternately spun optical fibers.

The optical fiber spans ...,  $305_{(k-1)}$ ,  $305_k$ ,  $305_{(k+1)}$ ,  $305_{(k+2)}$ ,  $305_{(k+3)}$ ,  $305_{(k+4)}$ ,  $305_{(k+5)}$ ,  $305_{(k+6)}$ , ..., are typically cabled and the optical fiber link **300** previously described is therefore typically part of an optical cable line. As  
15 schematically shown in **Figure 4B** (the drawing is not in scale), an optical cable line **80** typically comprises a plurality of trunks of optical cable ...,  $805_{(k-1)}$ ,  $805_k$ ,  $805_{(k+1)}$ ,  $805_{(k+2)}$ ,  $805_{(k+3)}$ ,  $805_{(k+4)}$ , ..., joined in series (i.e. concatenated) one to the other. Each cable trunk ...,  $805_{(k-1)}$ ,  
20  $805_k$ ,  $805_{(k+1)}$ ,  $805_{(k+2)}$ ,  $805_{(k+3)}$ ,  $805_{(k+4)}$ , ..., includes a respective optical fiber span ...,  $305_{(k-1)}$ ,  $305_k$ ,  $305_{(k+1)}$ ,  $305_{(k+2)}$ ,  $305_{(k+3)}$ ,  $305_{(k+4)}$ ,  $305_{(k+5)}$ ,  $305_{(k+6)}$ , ....

Each optical cable trunk ...,  $805_{(k-1)}$ ,  $805_k$ ,  $805_{(k+1)}$ ,  $805_{(k+2)}$ ,  $805_{(k+3)}$ ,  $805_{(k+4)}$ , ..., has a typical length in the  
25 range from approximately 2 km to approximately 10 km.

With reference to **Figure 4A**, a cross-sectional view of an optical cable along the optical cable line **80** is shown; the optical cable typically comprises an optical core **81** containing a plurality of optical fibers **800**.

30 The optical core **81** may be of the "tight" type (as the one illustrated in the drawing), wherein the optical fibers **800** are embedded into a polymeric matrix disposed around a strength member **83**, or of the "loose" type, wherein the

fibers 800 are loosely housed within a single buffer tube centrally disposed within said cable, or within a plurality of buffer tubes stranded around a central strength member. Around the optical core 81, the optical cable 80 is provided  
5 with reinforcing elements 84 and protective sheaths 85, 86.

In "tight" type cabling, the contact between the fiber and the polymeric matrix prevents the twist imparted to the fibers to be released. In "loose" type cabling, the twist imparted on the fiber is not released, for typical cable  
10 lengths, due to friction between the fiber and the buffer tube, possibly enhanced by the presence of a jelly filler.

From a manufacturing viewpoint, the optical fiber link 300 can be obtained starting by producing two sets of unidirectionally spun optical fibers having opposite  
15 spinning helicity. The two sets of fibers are properly labeled, for example  $\sigma_+$  and  $\sigma_-$ , so as to be able to distinguish fibers of one set from those of the other. Accordingly, the first set will be said to have a  $\sigma_+$  helicity and the second set a  $\sigma_-$  helicity.

20 Preferably, in order to ease the task of alternating fiber spans with mutually opposite spinning helicity, the unidirectionally spun optical fiber with  $\sigma_+$  helicity has substantially the same spin rate as the unidirectionally spun optical fiber with  $\sigma_-$  helicity.

25 Later on in the present description, an apparatus suitable to produce unidirectionally spun optical fibers will be described in detail, being intended that the way, and the apparatuses, by means of which the unidirectionally spun optical fibers are obtained are not limitative to the  
30 present invention.

Once two sets of fibers ( $\sigma_+$  and  $\sigma_-$ ) with opposite helicity have been produced, spans of predetermined length of these fibers are used in a cabling process of a known

type to produce an optical cable such as the one illustrated in **Figure 4A**.

A plurality of optical cable trunks is thus formed. These optical cable trunks are then connected one to another  
5 by known techniques, to form an optical cable transmission line such as the one illustrated in **Figure 4B**.

According to a first embodiment, each optical cable trunk may include, in its optical core, a certain number (for example, half of the total number) of fibers with a  
10 clockwise helicity and a certain number (for example, of half the total number) of fibers with a counter clockwise helicity. In this case, the optical cable trunks may be identical to each other.

According to a second embodiment, each optical cable  
15 trunks may include fibers of a single type, i.e. either of clockwise helicity or of counter-clockwise helicity. In this case, cable trunks including only  $\sigma_+$  fibers and cable trunks including only  $\sigma_-$  fibers are produced.

Then the optical cable trunks are concatenated to each  
20 other to form the optical cable line **80**. To join together two optical cable trunks, a connecting device of a known type can be used, such as the optical fiber connecting assembly described in the United States patent US 5,778,131 or the compact joint Oasys<sup>(R)</sup> realized by Pirelli. In  
25 practice, the fibers exiting the ends of the two cable trunks are housed and routed in the connecting device, and then they may be spliced end-to-end by a fusion splicer of a know type, such as model FSM-40S/40S-B by Fujikura.

The optical fiber spans ..., **305**<sub>(k-1)</sub>, **305**<sub>(k+1)</sub>, **305**<sub>(k+3)</sub>,  
30 **305**<sub>(k+5)</sub>, ..., are so spliced to form the optical fiber link **300**. In particular, the optical fiber link **300** is formed by splicing alternately a fiber span ..., **305**<sub>(k-1)</sub>, **305**<sub>(k+1)</sub>, **305**<sub>(k+3)</sub>, **305**<sub>(k+5)</sub>, ..., from the right-handed (left-handed)



spun fiber set  $\sigma_+$  ( $\sigma_-$ ), with a fiber span ...,  $305_k$ ,  $305_{(k+2)}$ ,  $305_{(k+4)}$ ,  $305_{(k+6)}$ , ..., from the left-handed (right-handed) spun fiber set  $\sigma_-$  ( $\sigma_+$ ).

By properly choosing the spin rate of the  $\sigma_+$  and  $\sigma_-$  optical fiber spans, in particular by making the transient characteristic length  $L_T$  suitably longer than the typical cable trunk length, the optical cable line obtained by joining optical cable trunks including optical fibers spans of opposite ( $\sigma_+$  and  $\sigma_-$ ) helicity has a low and substantially constant PMD<sub>c</sub>.

If the optical cable trunks include optical fiber spans of a same helicity (either right-handed, i.e.  $\sigma_+$ , or left-handed, i.e.  $\sigma_-$ ), the optical cable 80 is preferably made by alternating cable trunks including  $\sigma_+$  fiber spans with cable trunks including  $\sigma_-$  optical fiber spans.

Alternatively, if the optical cable trunks include both  $\sigma_+$  and  $\sigma_-$  optical fiber spans, the optical cable is preferably made by joining the different cable trunks in such a way that  $\sigma_+$  fibers spans are spliced with  $\sigma_-$  fiber spans.

The Applicant has investigated the PMD statistical properties of an optical fiber link such as the link 300.

It is known in the art that both unspun and alternately spun optical fibers present a Maxwellian statistical distribution of the DGD values. The Maxwellian distribution is characterized by a ratio between the average of the squared DGD,  $\langle \Delta\tau^2 \rangle$ , and the square of the averaged DGD,  $\langle \Delta\tau \rangle^2$ , equal to:

$$r = \frac{\langle \Delta\tau^2 \rangle}{\langle \Delta\tau \rangle^2} = \frac{3\pi}{8} \approx 1.18$$

In **Figure 5** the numerically computed (predicted) ratio  $r$  is plotted as a function of the propagating length. The

optical fiber link parameters are the same as for the fiber of the diagram of **Figure 3A**, with a span length  $L_c = 5$  km. The ratio  $r$  exhibits strong oscillations superimposed to a monotonous rise towards the asymptotic value, equal to 1.18.

5 A value of  $r$  larger than 1.18 indicates a statistical dispersion of the DGD values distribution larger than that typical of the Maxwellian distribution. On the other side, a value of  $r$  smaller than 1.18 indicates that the DGD values are less dispersed than in the Maxwell case.

10 **Figures 6A to 6F** are diagrams showing the statistical distribution of the DGD values at points (a) to (f) of **Figure 5**, respectively.

According to these results, an odd number of fiber spans joined together guarantees a Gaussian-like DGD  
15 statistical distribution narrower than the Maxwellian one, as shown in **Figures 6A-6D**, and correspondently in the points marked (a)-(d) in **Figure 5**. Here and in the following Figures, the dashed lines indicate the Maxwellian fit, and the solid lines the Gaussian fit. However, the narrowing of  
20 the distribution below the Maxwellian limit diminishes as the span number increases. On the other side, an even span number gives a DGD dispersion larger than, and asymptotically equal to, the Maxwellian distribution, as shown in **Figures 6E** and **6F**, and correspondently in the  
25 points marked as (e) and (f) in **Figure 5**.

The prediction of the DGD statistical distribution deviation mentioned in the introductory part of the present description is based on the following considerations. The statistical properties of the DGD are determined by the  
30 three stochastic Gauss-distributed components of the polarization dispersion vector  $\Omega_i$ , with  $i = 1, 2, 3$ , according to the formula (reported in a paper by A. Galtarossa et al, Optics Letters, Vol. 28, No. 18, September

2003):

$$DGD = \sqrt{\Omega_1^2 + \Omega_2^2 + \Omega_3^2}.$$

The  $PMD_c$  is the expectation value of the DGD statistical distribution, divided by the square root of the fiber length  
5 L.

In unidirectionally spun fibers,  $\Omega_3^2$  behaves markedly differently from  $\Omega_1^2$  and  $\Omega_2^2$ . For small  $z$  the DGD is mainly determined by the component  $\Omega_3^2$ , so that it tends to obey a Gauss-like distribution. As  $z$  increases,  $\Omega_1^2$  and  $\Omega_2^2$  catch-  
10 up, the three components tend to acquire the same statistical weight and the DGD becomes Maxwell-distributed.

In unidirectional fibers, the  $PMD_c$  increase with  $z$  follows from the (asymptotically linear) increase with  $z$  of the averages  $\langle \Omega_i^2(z) \rangle$ ,  $i=1,2,3$ . The Applicant has found  
15 that, by alternating spans of opposite helicity, these averages can be substantially reduced with respect to the single-helicity case, and that the shorter the span length, the stronger the reduction.

In the following, an apparatus and a method to produce  
20 unidirectionally spun optical fibers will be described in detail. It is understood that these apparatus and method are not limitative to the present invention, any other method, and apparatus, adapted to produce unidirectionally spun fibers being suitable.

25 With reference to **Figure 7**, a drawing tower **1** comprises a plurality of devices that are substantially aligned along a vertical drawing axis **2** (whence the term "tower"). The choice of a vertical direction in order to perform the main steps of the drawing process arises from the need to exploit  
30 the gravitational force so as to obtain, from a glass preform **3**, molten material from which an optical fiber **4** can be drawn.

In detail, the tower 1 comprises a furnace 6 for performing a controlled melting of a lower portion of the preform 3 (also known as preform neckdown), a feeding device 7 for supporting the preform 3 and feeding it into the  
5 furnace 6 from the above, a traction device 8 (at a lower end of the tower) for pulling the fiber 4 from the preform 3, and a winding device 9 for storing the fiber 4 onto a reel 10.

The furnace 6 may be of any type designed to produce a  
10 controlled melting of a preform. Examples of furnaces that can be used in the tower 1 are described in US 4,969,941 and US 5,114,338.

Preferably, a cooling device 12, for example of a type having a cooling cavity designed to be passed through by a  
15 flow of cooling gas, is situated underneath the furnace 6 for cooling the fiber 4 leaving it. The cooling device 12 is arranged coaxially to the axis 2, so that the fiber 4 leaving the furnace 6 can pass through it.

The tower 1 may also be provided with a tension-  
20 monitoring device 13 (for example of the type described in the United States patent US 5,316,562), and a diameter sensor 14 of a known type, preferably positioned between the furnace 6 and the cooling device 12, for measuring the tension and the diameter of the fiber 4, respectively.

25 Preferably, the tower 1 further comprises a first and a second coating devices 15, 16 of a known type, positioned underneath the cooling device 12 in the vertical drawing direction and designed to deposit onto the fiber 4, as it passes through, a first protective coating and,  
30 respectively, a second protective coating. Each coating device 15, 16 comprises, in particular, a respective application unit 15a, 16a which is designed to apply onto fiber 4 a predefined quantity of resin, and a respective

curing unit **15b**, **16b**, for example a UV-lamp oven, for curing the resin, thus providing a stable coating.

The traction device **8** may be of the single pulley or double pulley type. In the illustrated embodiment, the traction device **8** comprises a single motor-driven pulley (or "capstan") **18** that is designed to draw the fiber **4**, already coated, in the vertical drawing direction. The traction device **8** may be provided with an angular velocity sensor **19** that is designed to generate a signal indicating the angular velocity of the pulley **18** during its operation. The rotation speed of the pulley **18** and, therefore, the drawing speed of the fiber **4**, may be varied during the process, for example as a response to a diameter variation detected by detector **14**.

The tower **1** further comprises a spinning device **20**, positioned between the coating devices **15**, **16** and the traction device **8**, for imparting a spin to the fiber **4** about its axis during drawing. For the purposes of the present description, the term "spin" denotes the ratio (disregarding a constant multiplication factor) between the angular velocity of rotation  $dq/dt$  of the optical fiber (where  $q$  is the angle of rotation of the optical fiber measured with respect to a fixed reference point) and the velocity of drawing. The spin defined in this way is typically measured in turns/m.

In one possible embodiment, illustrated in **Figure 8**, the spinning device **20** comprises a fixed support frame **21**, a DC motor **22** held by the frame **21** and a rotating member **23** held by the frame **21** and coupled to the motor **22** through a belt transmission **24**. The belt transmission comprises a first driving pulley **24a** rigidly coupled to the motor **22**, a second driving pulley **24b** rigidly coupled to the rotating member **23** and a belt **24c** connecting the first driving pulley

**24a** to the second driving pulley **24b**.

The rotating member **23** has a rotation axis corresponding to the axis **2**, i.e. to the axis of motion of the fiber **4** when entering and leaving the device **20**. The  
5 rotating member **23** comprises a first and a second sleeve-like end portion **23a**, **23b** (respectively upper and lower), which are rotatably coupled to the support frame **21** by means of respective bearings **26** and which allows passage of the fiber there through. The second end portion **23b** is coupled  
10 with the second driving pulley **24b**.

The rotating member **23** comprises two arms **27a**, **27b**, extending from the first end portion **23a** to the second end portion **23b**. The arms **27a**, **27b** are substantially C-shaped, with a main straight central region parallel to the axis **2**,  
15 and are arranged symmetrically to each other with respect to the axis **2**. One of the two arms (the one indicated with **27b** in the drawing) carries a first, a second, and a third idle-mounted rotating pulley **28a**, **28b**, **28c** (from up to down in the drawing), substantially aligned in a direction parallel  
20 to the axis **2**. The three pulleys **28a**, **28b**, **28c** have the corresponding axes perpendicular to the axis **2** and are dimensioned so that the corresponding guiding grooves are substantially tangent to the axis **2**.

Referring back to **Figure 7**, the tower **1** may also  
25 comprise a tension-control device **30**, commonly known as "dancer", for adjusting the tension of the fiber **4** downstream the traction device **8**. The tension-control device **30** is designed to counterbalance any variations in tension of the fiber **4** between the pulley **18** and the winding device  
30 **9**. The tension-control device **30** may comprise, for example, a first and a second pulleys **30a**, **30b** that are mounted idle and in a fixed position, and a third pulley **30c** which is free to move vertically, under the action of its own weight

and the tension of the fiber 4. In practice, the pulley 30c is raised if there is an undesirable increase in the tension of the fiber 4 and is lowered if there is an undesirable decrease in the tension of the fiber 4, so as to keep the  
5 said tension substantially constant. The pulley 30c may be provided with a vertical position sensor (not shown) that is designed to generate a signal indicating the vertical position of the pulley 30c and therefore indicating the tension of the fiber 4.

10 One or more pulleys 31 (or guiding members of other types) are advantageously provided for guiding the fiber 4 from the tension-control device 30 to the winding device 9.

The winding device 9 comprises, in the illustrated embodiment, a first, a second, a third and a fourth guiding  
15 pulleys 36a, 36b, 36c, 36d, held by a support member 37, for guiding the fiber 4 onto the reel 10. The winding device 9 further comprises a motorized device 33 for setting the reel 10 into rotation about its axis 34. The motorized device 33 may also be suitable for reciprocating the reel 10 along the  
20 axis 34, so as to allow helix winding of the fiber 4 thereon during drawing. Alternatively, the reel 10 may be axially fixed and the support member 37 (together with the pulleys 36a, 36b, 36c, 36d) may be mounted on a motorized slide (not shown in the drawing) designed to reciprocate along an axis  
25 parallel to the reel axis 34.

A twist apparatus 40 is advantageously used for de-twisting the fiber, i.e. for removing an undesired elastic twist stored in the fiber 4 when spun. This undesired twist, which tends to generate circular birefringence in the fiber,  
30 is produced during spinning of the fiber due to the presence of a fiber rotation constraint downstream the point of spinning.

The twist apparatus 40 may be used at the drawing

stage, in particular to de-twist the fiber 4 during winding thereof, or it may be used at a subsequent stage, for example during unwinding of the fiber 4 for re-spooling it on a bobbin suitable for shipment, as will be described in  
5 the following.

In practice, the twist apparatus 40 expressly applies to the fiber a twist (which will be called "de-twist") in a direction opposite that of the undesired elastic twist resulting from spinning. In the following, with "direction  
10 opposite to the direction of spin", referred to the direction of the de-twist, it will be intended the direction opposite to the direction of the twist resulting from spinning. The twist apparatus 40 may advantageously be integrated in the winding device 9 of the drawing tower 1.  
15 In particular, the support member 37 and the pulleys 36a, 36b, 36c, 36d may be part of the twist apparatus 40. With reference to **Figure 9**, which illustrates one possible embodiment of the twist apparatus 40, the support member 37 is a rotating member having the shape of a two-prongs fork and comprising a hollow spindle 41 and a first and a second  
20 arms 45, 46 extending from one end 41a of the hollow spindle 41. The spindle 41 is held coaxial to the axis 34 by a fixed frame 43 and is rotatably mounted thereon through bearings 44. The spindle 41 is driven by a DC motor (not shown in the drawing) through a belt transmission (also not shown in the  
25 drawing). In use, the spindle 41 is designed to be passed through by the fiber 4 along the axis 34.

The first and second arms 45, 46 are symmetrical to each other with respect to the axis 34 and have respective  
30 first portions 45a, 46a rigidly connected to the spindle 41 and extending away from the axis 34 opposite to each other, and respective second portions 45b, 46b parallel to the axis 34. The first portions 45a, 46a have a radial extension



greater than the radius of the reel 10, and the second portions 45b, 46b have a length corresponding substantially to the length of the reel 10. The reel 10 is located between the second portions 45b, 46b of the arms 45, 46.

5       The first pulley 36a is positioned at the end of the spindle 41 facing the reel 10, and is designed to deviate the fiber 4 to the first arm 45. The second, third and fourth pulleys 36b, 36c, 36d are positioned along the second portion 45b of the first arm 45 and define a wavy path for  
10       the fiber 4 before it is fed to the reel 10. The function of the third pulley 36c (which is intermediate between the second pulley 36b and the fourth pulley 36d) is to avoid that the fiber 4 slips from pulleys 36b and 36d, and it might be dispensed for. The second arm 46 has only a  
15       balancing function and may carry three pulleys identical to pulleys 36b, 36c, 36d, to have the same distribution of weights as the first arm 45.

      While the first, second and third pulleys 36a, 36b, 36c preferably have the respective axes parallel to each other  
20       and perpendicular to the axis 34, the fourth pulley 36d is preferably tilted about an axis parallel to the axis 34, of such an angle that it lies on a plane that is tangent to the fiber bobbin when the reel 10 is half filled.

      The twist apparatus 40 preferably comprises a fiber  
25       position sensor 48 (for example a device model Keyence FS-V11P FU-35FA) positioned between the fourth pulley 36d and the reel 10, to provide a control signal for the alternate axial motion of the reel 10 (Figure 9 shows, for example, two different positions of reel 10) or of the support member  
30       37. In fact, as previously stated, a relative alternate motion shall be provided between the reel 10 and the support member 37 to allow helix winding of the fiber 4.

      The drawing tower 1 may further comprise a control unit

(not shown in the drawing), electrically connected to all the devices of the tower 1 to be controlled from the outside, and to all the sensors and the detectors present along the tower 1.

5       The drawing tower 1 operates as follows.

      The supporting device 7 feeds the preform 3 to the furnace, where a lower portion thereof (the neckdown) is melted. The fiber 4 drawn from the neckdown is pulled down from the traction device 8 and wound onto the reel 10 by the  
10       winding device 9. Between the capstan 18 and the reel 10, the tension-control device 30 regulates the tension of the fiber 4.

      As the fiber 4 is drawn, the sensors 13 and 14 monitor its tension and diameter. Such monitoring can be used to  
15       control the drawing process, for example by acting on the traction speed. When exiting the furnace 6, the fiber 4 is cooled by the cooling device 12 and it is coated with two protective layers by the coating devices 15, 16.

      The coated fiber 4 is then subjected to a  
20       unidirectional and substantially constant spin by the spinning device 20. This is obtained by setting into rotation the rotating member 23 about the axis 2 at a constant speed. Each turn of the rotating member corresponds to one turn of the fiber 4 about its axis.

25       The spin rate is selected in such a way that the effects of the imperfections and irregularities of the fiber 4 are rendered substantially uniform in a length of the fiber 4 equal to at least the shortest typical beat length  $L_B$ . As a result, when signals are transmitted into the  
30       fiber, there is an exchange of power between the fundamental propagation modes and, therefore, a reduction of the PMD. Thus, it is possible to significantly reduce the negative effects caused by the asymmetric stress conditions and by

the imperfections of shape intrinsically present in the fiber 4.

The Applicant has observed that the higher the spin rate, the better the performances of the fiber in terms of PMD. However, the higher the spin rate, the higher the elastic twist to be removed. The Applicant has verified that a spin rate between 1 and 8 turns/m allows reducing the PMD at acceptable values and at the same time introduces an amount of elastic twist that can be efficiently removed by the technique here described.

When spun, the fiber 4 transmits a corresponding torque upstream and downstream. Upstream, the torque is transmitted to the preform neckdown, where the plastic deformation of the melted glass "absorbs" the torque and "transforms" it into an intrinsic orientation of the birefringence axes of the fiber 4. This intrinsic torsion is frozen into the fiber 4 as the fiber cools. Downstream, in the absence of any countermeasure, the torque would be transmitted as far as the reel 10, where the fiber 4, once wound, would keep a residual elastic twist. This elastic twist would introduce, if not controlled, an undesired circular birefringence in the fiber 4.

In order to control the residual twist in the wound fiber 4, the fiber 4 is de-twisted by the twist apparatus 40. In practice, the rotating support member 37 is made to rotate about the axis 34, in a sense opposite to the spinning sense (more precisely, as previously stated, in a sense opposite to that of the elastic twist generated by spinning). Each turn of the support member 37 about the axis 34 corresponds to one turn of the fiber 4 about its axis. The torque transmitted along the fiber 4 downstream the spinning device 20 is then at least reduced by the twist apparatus 40 before the fiber is wound onto the reel 10.

In detail, the fiber 4, after passing through the spindle 41, is deviated by the first pulley 36a towards the first arm 45, is herein conveyed along the second portion 45b with the required tension by the second and third  
5 pulleys 36b, 36c, and is finally fed to the reel 10 by the fourth pulley 36d, in a direction substantially perpendicular to the axis 34. While being rotated about the axis 34, the reel 10 is also reciprocated along the axis 34, so as to allow an helical winding of the fiber 4.

10 The signal of the sensor 48 is used to control the speed of the alternate motion of the reel 10, so that the fiber 4 is always made to pass in a predetermined position of the sensor 48.

The Applicant has found that the PMD of the fiber 4 can  
15 be reduced to a minimum by imparting to the fiber, after it has been spun, a twist that not only removes the elastic twist generated by the spinning action, but also introduces a positive residual twist, i.e. a twist in the opposite sense. The Applicant has verified that a positive residual  
20 twist between 0 and 1.5 turns/m, preferably between 0.3 and 1 turns/m, allows reducing the PMD of spun fibers in a wide range of spin rates, at least up to 8 turns/m.

As previously stated, fiber de-twisting may be performed, instead of during the drawing process, at a stage  
25 subsequent to drawing, and may be associated with the operation of unwinding of the fiber 4 from reel 10. For example, de-twisting may be performed during re-spooling of the fiber 4 onto a shipping spool to be shipped to a customer or during screening operations. Screening is a test  
30 operation, performed on an optical fiber to check the strength thereof, which comprises applying a predetermined longitudinal tension to the fiber 4 while it runs in a predetermined path, usually defined by pulleys.

As shown in **Figure 10**, the twist apparatus **40** may for example be used with the fiber **4** moving in the opposite direction, so as to perform fiber de-twisting while the fiber **4** is unwound. In particular, **Figure 10** illustrates a re-spooling assembly **70** comprising an unwinding device **9'** for unwinding the fiber **4** from the reel **10** and a further winding device **71**, including guiding pulleys **73**, for re-winding the fiber **4** onto a different reel **74**. The unwinding device **9'** substantially corresponds to winding device **9**, but operates in the opposite direction, to unwind the fiber **4**. In this case, the twist apparatus **40** is integrated in the unwinding device **9'** for de-twisting the fiber **4** as it is unwound from the reel **10**. The re-spooling assembly **70** may also comprise a screening device **72**, for example of the type described in US 5,076,104.

**Figure 11** shows a different embodiment of the twist apparatus, indicated with reference numeral **50**. The twist apparatus **50** comprises a fixed frame **51** supporting the reel **10** along the axis **34**, and a rotating member **52** for twisting the fiber **4** as it is wound onto the reel **10** or unwound therefrom.

The rotating member **52** comprises a first and a second spindles **53**, **54**, supported by the frame **51** coaxially to the axis **34**, and a flexible arch member **55** connecting the two spindles **53**, **54** over the reel **10**, for the passage of the fiber **4**.

The fixed frame **51** comprises two external support members **56**, **57** and two internal support members **58**, **59** substantially aligned to each other along the axis **34**. The external support members **56**, **57** are cylindrical and the member **57** has an internal passage for the fiber **4**, along the axis **34**. The reel **10** is positioned between the internal support members **58**, **59** and it is supported thereby. The reel

10 is connected to a motor (not shown in the drawing) through a belt transmission 60.

5 The spindles 53, 54 are opposite to each other with respect to the reel 10 and are connected to a same motor (different from that of the reel 10 and not shown in the drawing) through respective belt transmissions 62 (only one of which is illustrated), so that they can be rotated at a same speed. Each of the spindles 53, 54 is positioned between a corresponding external support member 56, 57 and a  
10 corresponding internal support member 58, 59. The first spindle 53 carries internally a pulley 67 tangent to the axis 34 that allows the passage of the fiber 4 between the arch member 55 and a further pulley 69 tangent to the axis 34 carried by the internal support member 58. The second  
15 spindle 54 carries internally a further pulley 68 tangent to the axis 34 allowing the passage of the fiber 4 between the external support member 57 and the arch member 55. One or more further pulleys are provided for guiding the fiber to or from the reel 10.

20 The flexible arch member 55 is preferably made of carbonium and forms a bridge over the reel 10 for the passage of the fiber 4 between the spindles 53, 54. The arch member 55 may be provided with equidistant guiding U-bolts 61, preferably made of ceramic and suitable to guide the  
25 fiber 4 along the arch member 55. Alternatively, the arch member 55 may be provided with a guiding tube (not shown in the drawing), which offers the advantage of an easier set-up before the process start, allowing blowing of the fiber 4 from one end to the other of the arch member 55.

30 The apparatus 50 is herein below described when operating for winding the fiber onto the reel 10. Similarly to the apparatus 40, the apparatus 50 may operate in the opposite direction to unwind the fiber 4 from the reel 10,

for example in the re-spooling assembly 70 of **Figure 10**.

5 The fiber 4 is received through the member 57 and a first portion of the second spindle 54, where it is deviated by the pulley 68 to the arch member 55; the fiber 4 then runs over the entire arch member 55 and enters the first spindle 53, where it is further deviated by the pulley 67 towards the internal support member 58 along the axis 34; then, the fiber is further deviated by the pulley 69 and it is finally fed to the reel 10.

10 The amount of twist to be applied to the optical fiber 4 for obtaining the desired amount of residual twist may be determined according to the following technique. In a first step, a test fiber section only subjected to spin is drawn. This test fiber section can be obtained, for example, by  
15 operating the drawing tower 1 of **Figure 7** with the twist apparatus 40 off (i.e. with the rotating member 37 in a staying condition) for a predetermined time. Then, the residual twist accumulated in the test fiber section wound on the reel 10 is measured in the following way.

20 The reel 10 is hanged on a support located at a predetermined height, for example at 2 m above ground. A corresponding length of fiber is unwound from the reel 10, keeping it under a moderate tension. The upper end of the unwound fiber section is secured to the reel surface, while  
25 the free end is marked, for example with a small piece of tape (having a negligible weight) and it is left free to rotate. The measurement resolution depends on the length of the unwound fiber section. For a fiber length of 2 m, the number of turns can be measured with a resolution of about  $\frac{1}{4}$   
30 turns over 2 m, so that a resolution of about 0.125 turns/m can be obtained. If a higher resolution is required, a longer fiber can be used.

The Applicant has observed that the presence of the

fiber coating shall be taken into consideration for an accurate measurement of the residual twist due to spinning, since a residual twist is also accumulated in the fiber under the coating. Accordingly, after the residual twist of the coated fiber has been measured in the way previously described, the free end of the coated fiber is blocked and the coating is completely removed (using a conventional Miller stripper). The fiber is then left again free to rotate, and the additional rotation of the fiber is measured with the same resolution as above.

The operation is repeated over consecutive fiber sections of predetermined length, for example every 2 m, to reach a predetermined total measured length, for example between 20 and 60 m. The mean value is used to label the torsion value of the fiber.

After the residual twist due to spinning has been measured, the fiber drawing may be continued with the twist apparatus 40 turned on, suitably set to obtain the desired residual twist.

It is thus possible to obtain an optical fiber having a unidirectional intrinsic spin and an elastic twist equal to zero in module, or opposite to said spin and greater than zero in module.

The unidirectional intrinsic spin may be substantially constant or variable. In this second case, the spin function is preferably obtained by superposing a substantially constant function and a periodic function, and the twist is applied so as to vary the average value of the residual twist to the desired value. The elastic twist applied to the fiber is preferably comprised in module between 0 and about 1.5 turns/m, more preferably between about 0.3 and 1 turns/m.

Fibers with both helicities, clockwise and counter



clockwise, are produced by the process previously described by changing the rotation direction of the spinning device and of the twisting device. Once two sets of fibers ( $\sigma_+$  and  $\sigma_-$ ) with opposite helicity have been produced, spans of  
5 predetermined length of these fibers are used in a cabling process of a known type to produce an optical cable as previously described.

Although the present invention has been disclosed and described by way of some embodiments, it is apparent to  
10 those skilled in the art that several modifications to the described embodiments, as well as other embodiments of the present invention are possible without departing from the scope thereof as defined in the appended claims.

For example, although in the invention embodiment shown  
15 in **Figure 2** a strict alternation of unidirectionally spun fiber spans having mutually opposite spinning helicity is provided for, this is not to be construed as a limitation of the present invention, because an optical fiber link might also be produced by splicing unidirectionally spun optical  
20 fiber spans of opposite spinning helicity without necessarily respecting such a strict alternation.

Moreover, the optical fiber link may comprise one or more spans of unspun optical fibers or of alternately spun optical fibers, spliced to the unidirectionally spun fibers  
25 or arranged between two spans of unidirectionally spun fiber.

#### Experimental results

The Applicant has experimentally confirmed the predicted PMD<sub>c</sub> increase in unidirectionally spun fibers.

30 To do this, two G.652 fibers have been drawn at a unidirectional spin rate of +3turns/m and -3turns/m, and completely de-twisted after the drawing process, in order to eliminate any residual elastic twist. The fibers have then

be loosely wound about a large diameter bobbin, and, to ensure that all the possible range of DGD values is explored, repeated DGD measurements have been performed, each time slightly perturbing the fiber deployment. In particular, the measure has been realized according to the Jones Matrix Eigenanalysis technique, using a PAT9200 polarimeter and a Tunics-Plus tunable laser. The wavelengths range from 1530 nm to 1620 nm has been scanned using a 10 nm step. Up to 1200 DGD values in one-hour time have been thus obtained. Circles and squares in **Figure 12** shows the measured PMDc as a function of  $z$  for the +3turns/m and -3turns/m fibers, respectively: it can be appreciated that the PMDc increases with the propagation distance, and converges to an asymptotic value, in agreement with the predictions reported in the afore-mentioned paper by A. Galtarossa et al. "Polarization mode dispersion properties of constantly spun randomly birefringent fibers", Optics Letters, vol 28 No.18, September 2003.

The Applicant has also experimentally confirmed the deviation of the DGD statistical distribution from the typical Maxwell distribution that was suggested in the same paper as affecting short spans of unidirectionally spun fibers. Referring to **Figures 13A to 13D**, which show the measured DGD distributions of the +3turns/m fiber of **Figure 12** for  $z = 1, 2, 3$ , and 4 km respectively, (in the diagrams, the solid and the dashed lines represent the Maxwell and the Gauss fits, respectively; the  $x$  and  $y$  axis represent the DGD (in ps) and the counts), it can be appreciated that unidirectional spinning may indeed severely affect the DGD statistics. In particular, for short values of  $z$  the DGD distribution is well fitted by a very narrow Gauss curve, with a ratio  $R$  (ratio between the expectation value and the standard deviation) much higher than 2.4, which is the  $R$

value of the Maxwell distribution. As  $z$  increases, the dispersion of the data around the expectation value increases (the ratio  $R$  decreases), and at the same time the distribution becomes more and more Maxwell-like.

5       The Applicant has experimentally confirmed the PMD growth reduction achievable by concatenating fiber spans of opposite helicity. Triangles in **Figure 12** report the experimentally measured  $\text{PMD}_c$  in fibers made by splicing alternated, 1-Km long spans of unidirectionally spun fiber  
10 of opposite helicity. In particular, samples of 1 Km of the aforementioned G.652 have been spliced together, having care to alternate the helicity. It can be appreciated that the  $\text{PMD}_c$  stabilizes to a value of about  $0.03 \text{ ps/km}^{1/2}$ .

15       The  $\text{PMD}_c$  measured at the splicing points exhibits an oscillating behavior with  $z$ , with the minima and the maxima corresponding to an even and to an odd number of spans, respectively. As indicated by the values of the ratio  $R$  (reported aside the triangles), the concatenation of an odd number of spans always gives a DGD dispersion greater than  
20 the concatenation of an even number. As  $z$  increases and the  $\text{PMD}_c$  tends to stabilize, the DGD distribution becomes larger and Maxwell-shaped, and the value of  $R$  decreases down to 2.4.

25       Splicing together alternated fiber spans of 2 Km, the  $\text{PMD}_c$  tends to a value of about  $0.04 \text{ ps/km}^{1/2}$ , while alternating spans of 3 Km does not provide a significant  $\text{PMD}_c$  reduction with respect to the unidirectionally spun fiber. Thus, fiber span length equal to or lower than 1 Km seems to provide good results, at least in the fiber herein  
30 considered.

#### Numerical results

The Applicant has numerically verified all these experimental observations with a code based on the random

modulus model of the fiber birefringence (RMM) and is explained in P.K.A. Wai and C.R. Menyuk, "Polarization Mode Dispersion, Decorrelation, and Diffusion in Optical Fibers with Randomly Varying Birefringence", Journal of Lightwave Technology, Vol. 14, No. 2, February 1996. The simulations confirmed that the PMDc compensation holds for an arbitrary number of alternated spans, so that a fiber of any length with a controlled PMDc value can be manufactured. The shorter the spans length, the smaller the asymptotic PMDc value.

In **Figure 12** the dashed, dotted and solid lines represent the result of RMM numerical simulation of the unidirectional +3turns/m fiber, unidirectional -3turns/m fiber and concatenated alternating helicity ( $\pm 3$ turns/m) link, respectively. The fit with experimental data is very good. The fibers parameters used for the simulations are the following:

- for the +3turns/m fiber and for the +3 turns/m spans in the alternated-helicity link:  $L_B=4m$ ,  $L_F=2.34m$ ;
- for the -3 turns/m fiber and for the -3 turns/m spans in the alternated-helicity link:  $L_B=5.6m$ ,  $L_F=3.45m$ .

CLAIMS

1. An optical fiber link (300) comprising a plurality of optical fiber spans (305<sub>(k-1)</sub>, 305<sub>k</sub>, 305<sub>(k+1)</sub>, 305<sub>(k+2)</sub>,  
5 305<sub>(k+3)</sub>, 305<sub>(k+4)</sub>, 305<sub>(k+5)</sub>, 305<sub>(k+6)</sub>) joined one to the other,  
characterized in that .

said plurality of optical fiber spans includes at least one first unidirectionally-spun optical fiber span (305<sub>(k-1)</sub>, 305<sub>(k+1)</sub>, 305<sub>(k+3)</sub>, 305<sub>(k+5)</sub>) and at least one second  
10 unidirectionally-spun optical fiber span (305<sub>k</sub>, 305<sub>(k+2)</sub>, 305<sub>(k+4)</sub>, 305<sub>(k+6)</sub>) having mutually opposite spinning directions.

2. The optical fiber link according to claim 1, in  
15 which the first unidirectionally-spun optical fiber span and the second unidirectionally-spun optical fiber span are joined to each other.

3. The optical fiber link according to claim 1, in  
20 which said plurality of optical fiber spans includes a plurality of first optical fiber spans, and a plurality of second optical fiber spans, the first optical fiber spans and the second optical fiber spans being spans of unidirectionally spun optical fibers having mutually  
25 opposite spinning directions, and wherein the first optical fiber spans and the second optical fiber spans are alternated to each other in the optical fiber link.

4. The optical fiber link according to claim 1, in  
30 which the first unidirectionally-spun optical fiber span and the second unidirectionally-spun optical fiber span have substantially a same span length.

5. The optical fiber link according to claim 1, in which each of said first and second unidirectionally-spun optical fiber spans have a span length, a spinning period  $p$ ,  
5 a correlation length  $L_F$  and a beat length  $L_B$ , and said span length is lower than 10 times the transient characteristic length  $L_T$  defined as

$$L_T = L_F \left( 1 + \frac{4L_B^2}{p^2} \right).$$

10 6. The optical fiber link according to claim 4 or 5, in which said span length is equal to or lower than approximately 3 Km.

15 7. The optical fiber link according to claim 6, in which said span length is equal to or lower than approximately 1 Km.

8. The optical fiber link according to claim 1, in which the first unidirectionally-spun optical fiber span and  
20 the second unidirectionally-spun optical fiber span have substantially a same spin rate.

9. The optical fiber link according to claim 3, in which the number of first optical fiber spans and second  
25 optical fiber spans is odd.

10. An optical cable line (80) including a plurality of optical cable trunks ( $805_{(k-1)}$ ,  $805_k$ ,  $805_{(k+1)}$ ,  $805_{(k+2)}$ ,  
30  $805_{(k+3)}$ ,  $805_{(k+4)}$ ) joined to each other, characterized in that said plurality of optical cable trunks comprises at least a first optical cable trunk and a second optical cable trunk, the first optical cable trunk including a first optical

fiber span  $(305_{(k-1)}, 305_{(k+1)}, 305_{(k+3)}, 305_{(k+5)})$  unidirectionally-spun in a first direction, and the second optical cable trunk including a second optical fiber span  $(305_k, 305_{(k+2)}, 305_{(k+4)}, 305_{(k+6)})$  unidirectionally-spun in a second direction opposite to the first direction, the first and the second optical fiber spans being optically linked to each other.

11. The optical cable line according to claim 10, in which the first and the second optical fiber spans are joined to each other.

12. The optical cable line according to claim 10, in which the first and the second optical fiber spans have substantially a same span length.

13. The optical cable line according to claim 10, in which each of said first and second optical fiber spans have a span length, a spinning period  $p$ , a correlation length  $L_F$  and a beat length  $L_B$ , and said span length is lower than about 10 times the transient characteristic length  $L_T$  defined as

$$L_T = L_F \left( 1 + \frac{4L_B^2}{p^2} \right).$$

14. The optical fiber link according to claim 12 or 13, in which said span length is equal to or lower than approximately 3 Km.

15. The optical fiber link according to claim 14, in which said span length is equal to or lower than approximately 1 Km.

16. The optical cable line according to claim 10, in which the first and the second optical fiber spans have substantially a same spin rate.

5        17. The optical cable line according to claim 10, in which the plurality of optical cable trunks include a plurality of first optical fiber spans ( $305_{(k-1)}$ ,  $305_{(k+1)}$ ,  $305_{(k+3)}$ ,  $305_{(k+5)}$ ), and a plurality of second optical fiber spans ( $305_k$ ,  $305_{(k+2)}$ ,  $305_{(k+4)}$ ,  $305_{(k+6)}$ ) joined to each  
10 other to form an optical fiber link (800), the first optical fiber spans and the second optical fiber spans being unidirectionally-spun optical fibers having mutually opposite spin directions, and wherein the first optical fiber spans and the second optical fiber spans are  
15 alternated to each other in the optical fiber link.

18. The optical cable line according to claim 10, in which at least one optical cable trunk of said plurality of optical cable trunks has an optical core including a  
20 plurality of unidirectionally-spun optical fiber spans having a same spin direction.

19. The optical cable line according to claim 10, in which at least one optical cable trunk of said plurality of  
25 optical cable trunks has an optical core including at least two unidirectionally-spun optical fiber spans having opposite spin directions.

20. The optical cable line according to claim 10, in  
30 which the total number of optical cable trunks is odd.

21. A method of realizing an optical fiber link (300), comprising:



providing at least a first span of optical fiber (305<sub>(k-1)</sub>, 305<sub>(k+1)</sub>, 305<sub>(k+3)</sub>, 305<sub>(k+5)</sub>), unidirectionally-spun in a first direction;

5 providing at least a second span of optical fiber (305<sub>k</sub>, 305<sub>(k+2)</sub>, 305<sub>(k+4)</sub>, 305<sub>(k+6)</sub>), unidirectionally-spun in a second direction opposite to the first direction; and

joining the first span and the second span together at a respective end thereof.

10 22. A method of producing an optical cable, comprising providing a plurality of optical fibers to a cable manufacturing line, wherein said plurality of optical fibers comprises at least a first optical fiber (305<sub>(k-1)</sub>, 305<sub>(k+1)</sub>, 305<sub>(k+3)</sub>, 305<sub>(k+5)</sub>) being unidirectionally-spun in a  
15 first direction, and at least a second optical fiber (305<sub>k</sub>, 305<sub>(k+2)</sub>, 305<sub>(k+4)</sub>, 305<sub>(k+6)</sub>) being unidirectionally-spun in a second direction opposite to the first direction.

20 23. A method of realizing an optical cable line, comprising:

forming a plurality of optical cable trunks (805<sub>k</sub>, ..., 805<sub>(k+4)</sub>), each one including at least one optical fiber span (305<sub>(k-1)</sub>, ..., 305<sub>(k+6)</sub>); and

joining the optical cable trunks one to another;

25 characterized in that

the step of forming a plurality of optical cable trunks comprises forming at least one first trunk including a first optical fiber span (305<sub>(k-1)</sub>, 305<sub>(k+1)</sub>, 305<sub>(k+3)</sub>, 305<sub>(k+5)</sub>) unidirectionally-spun in a first direction, and forming at  
30 least one second trunk including a second optical fiber span (305<sub>k</sub>, 305<sub>(k+2)</sub>, 305<sub>(k+4)</sub>, 305<sub>(k+6)</sub>) unidirectionally-spun in a second direction opposite to the first direction, and in that said joining the optical cable trunks one to another

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includes optically linking the first optical fiber span to  
said second optical fiber span.

LOW PMD OPTICAL FIBER LINK, AND METHOD OF MAKING THE SAME

\* \* \* \* \*

ABSTRACT

An optical fiber link (300) comprises a plurality of  
5 optical fiber spans ( $305_{(k-1)}, \dots, 305_{(k+6)}$ ) joined one to the  
other, the plurality of optical fiber spans including at  
least one first unidirectionally-spun optical fiber span  
( $305_{(k-1)}, 305_{(k+1)}, 305_{(k+3)}, 305_{(k+5)}$ ) and at least one second  
unidirectionally-spun optical fiber span  
10 ( $305_k, 305_{(k+2)}, 305_{(k+4)}, 305_{(k+6)}$ ) having mutually opposite  
spinning directions.

(Figure 2)

15

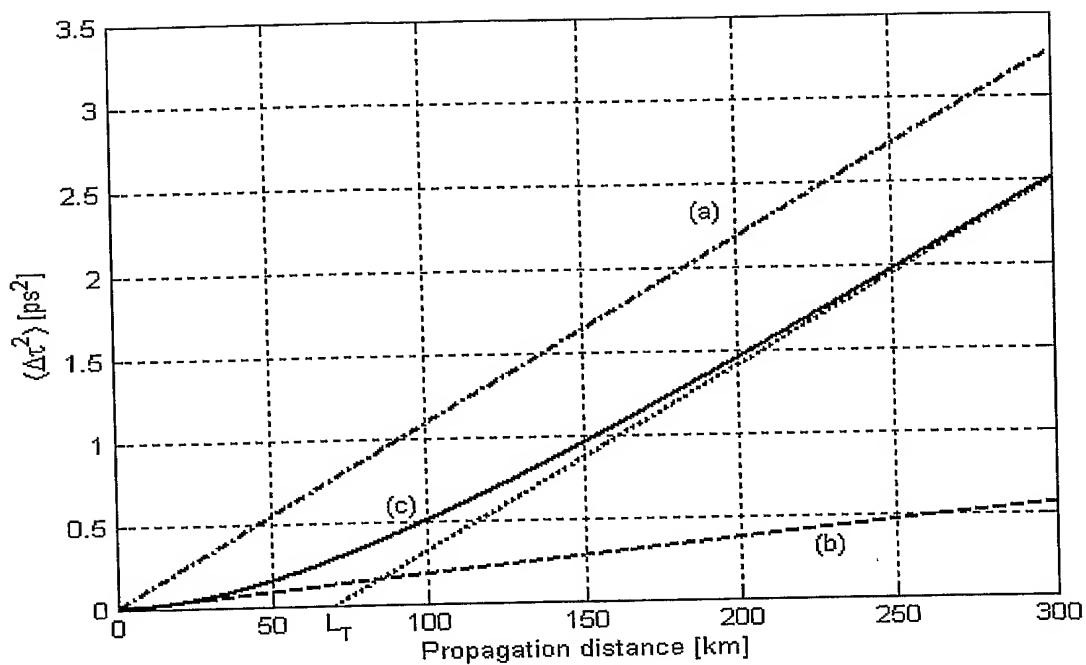


FIG. 1

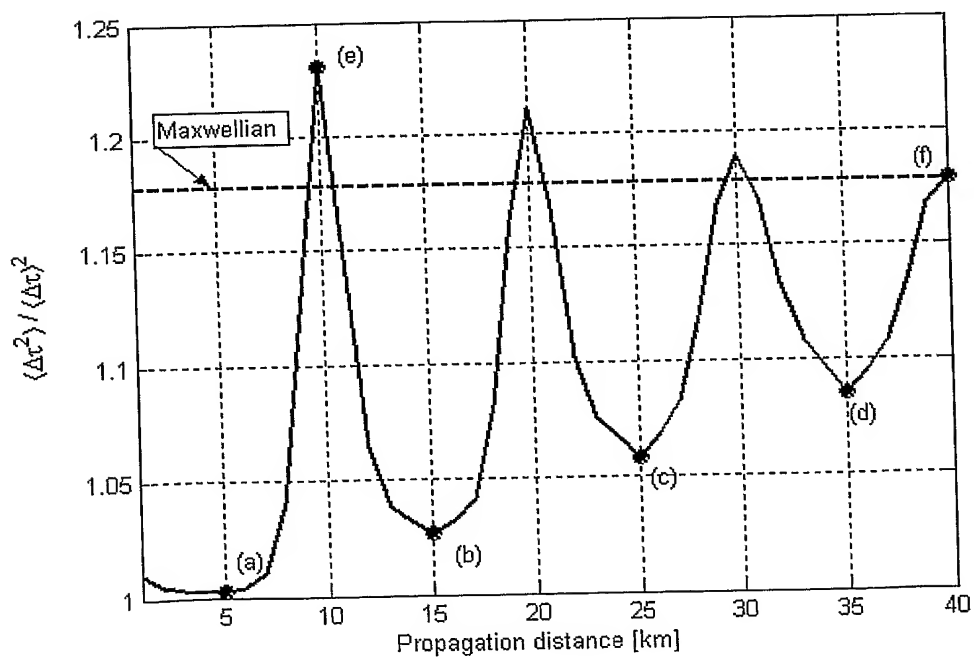


FIG. 5

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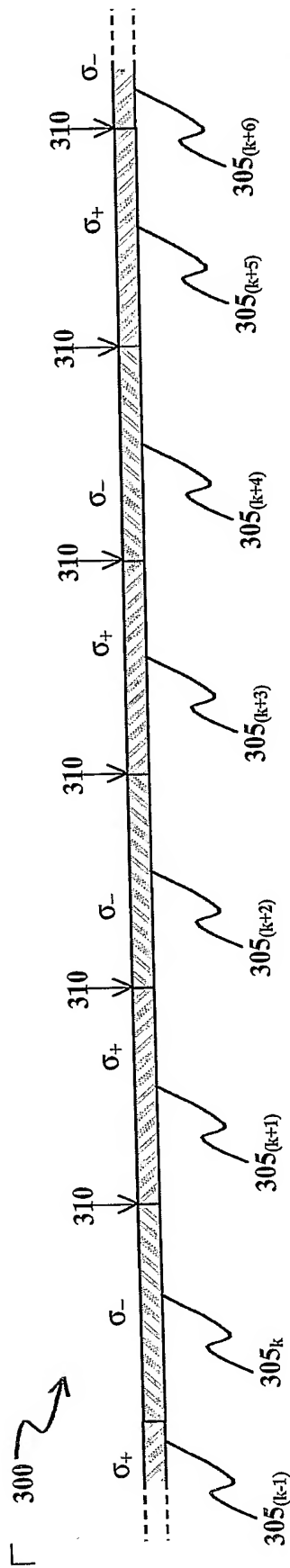


FIG. 2

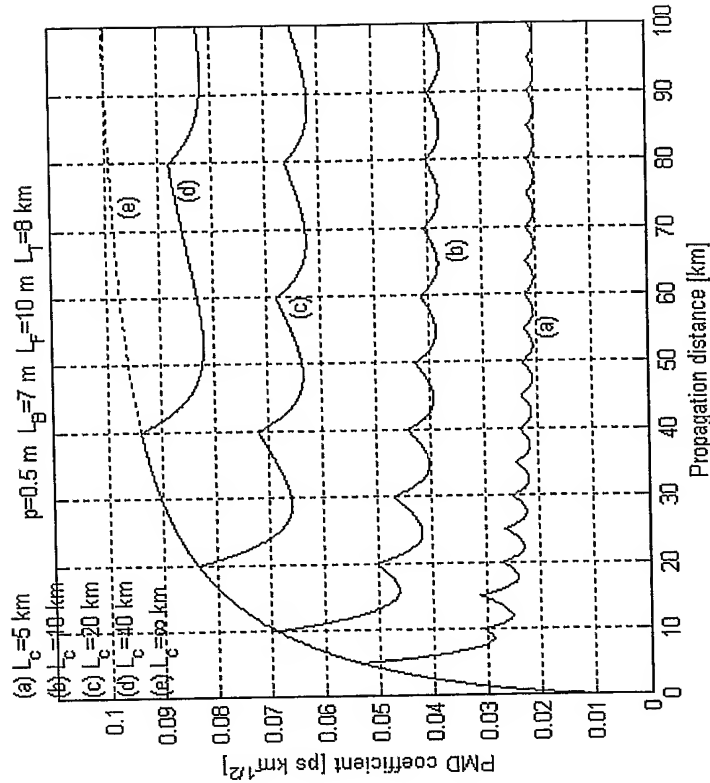


FIG. 3B

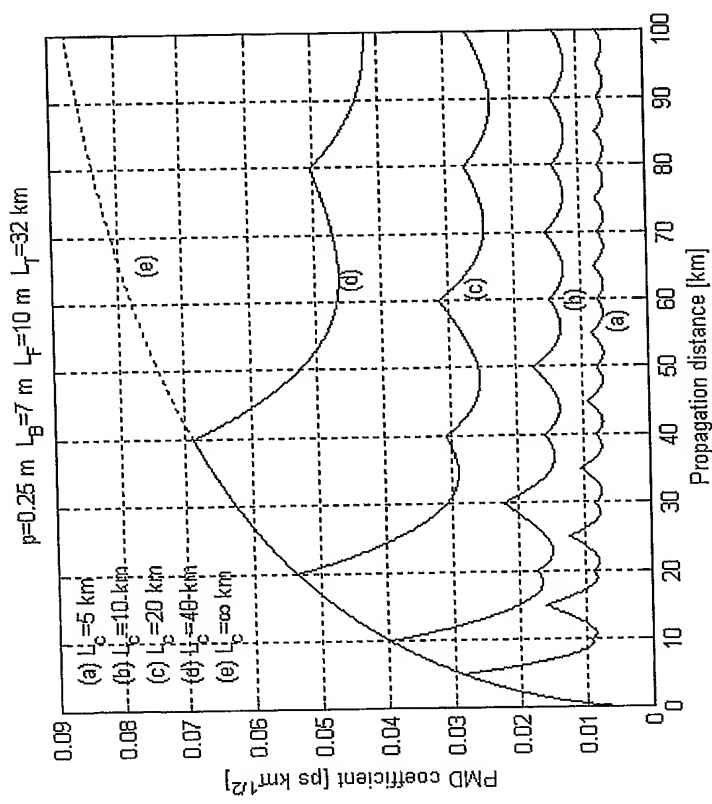


FIG. 3A

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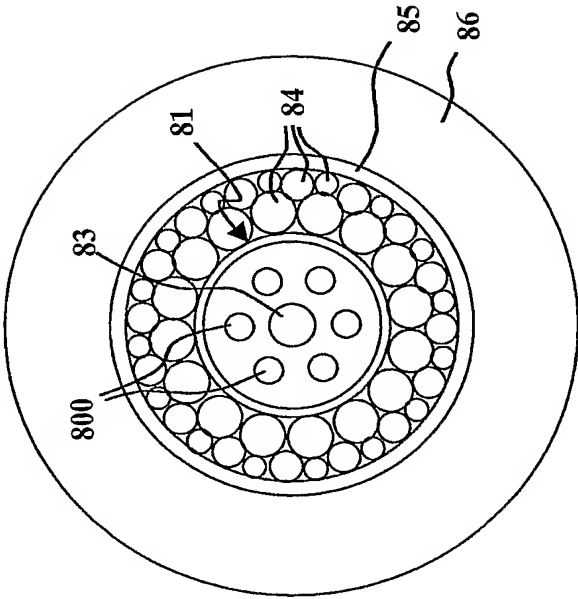


FIG. 4A

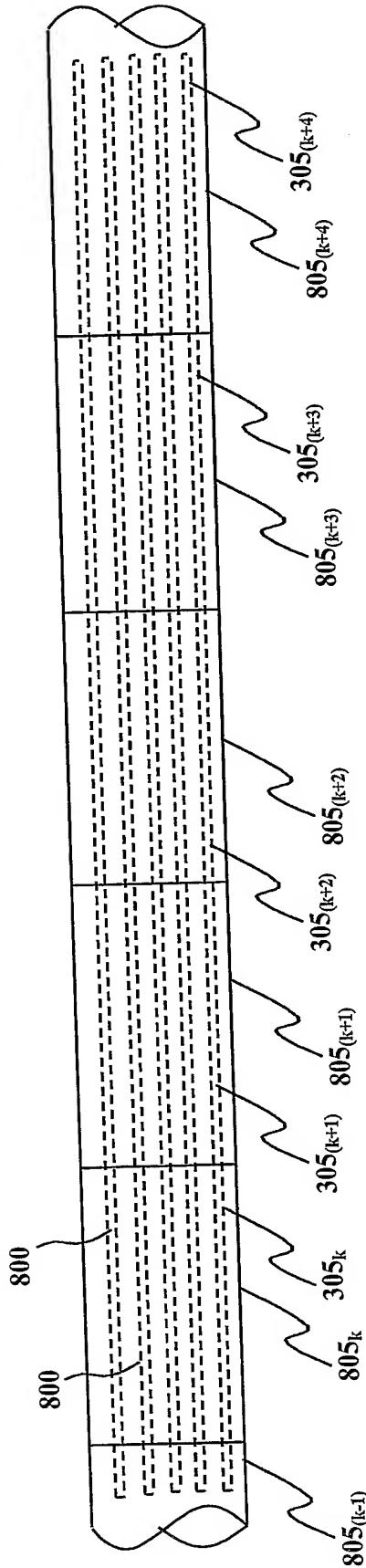


FIG. 4B

FIG. 6A

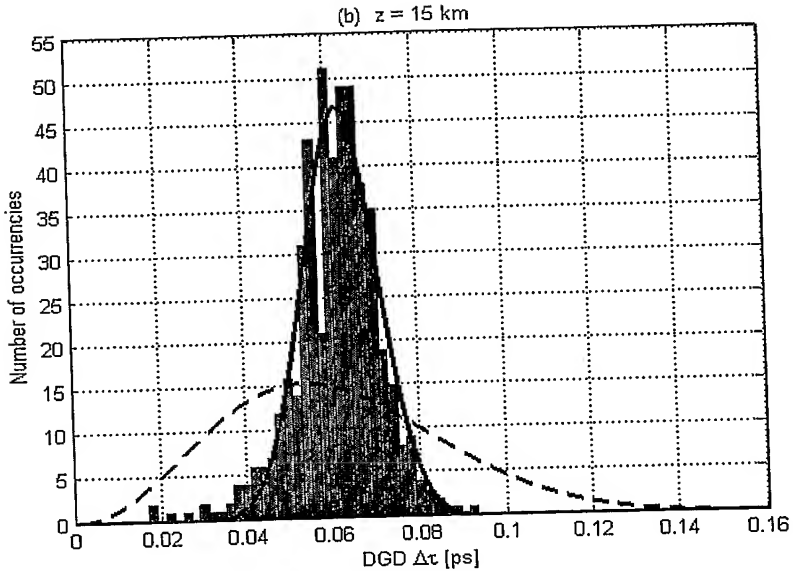
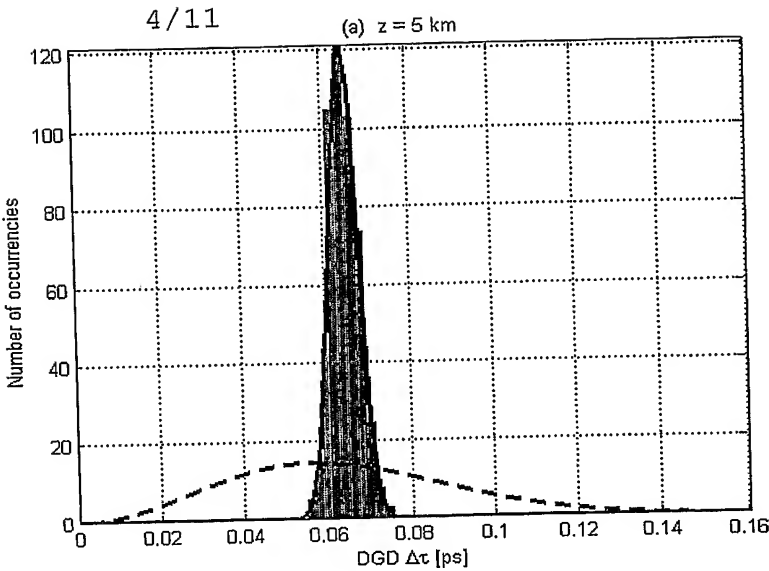


FIG. 6B

FIG. 6C

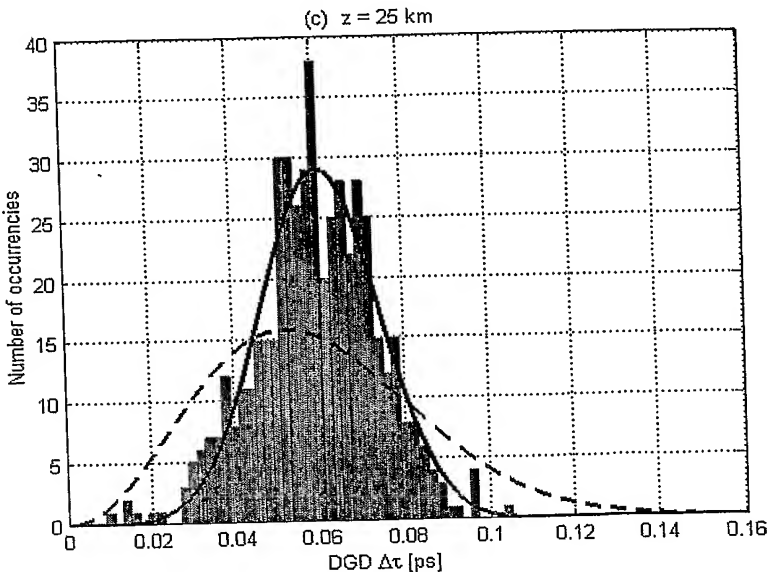


FIG. 6D

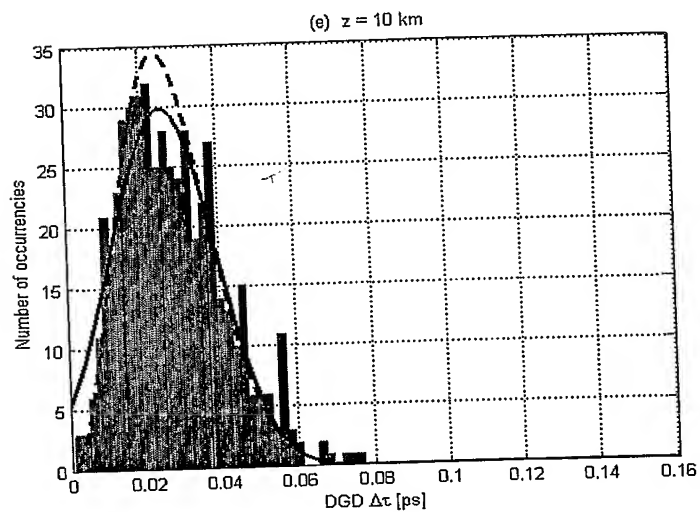
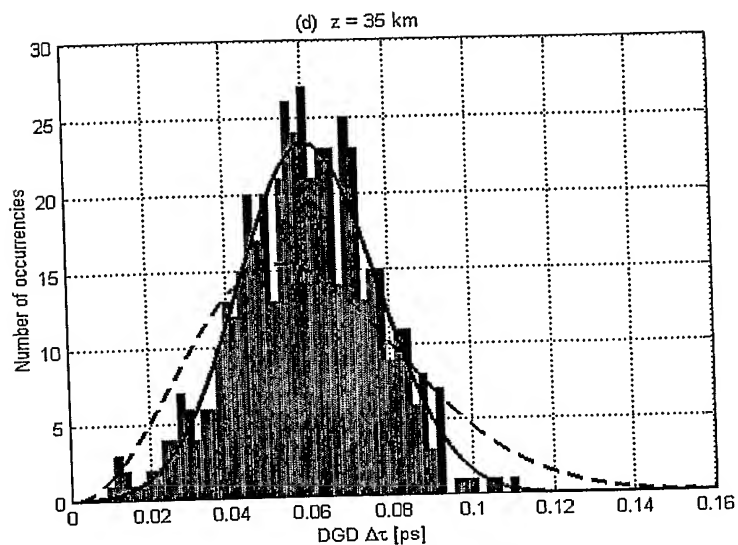
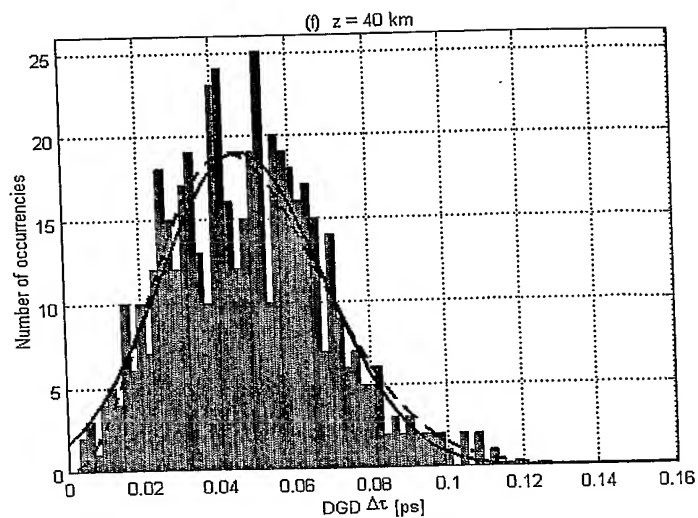


FIG. 6E

FIG. 6F





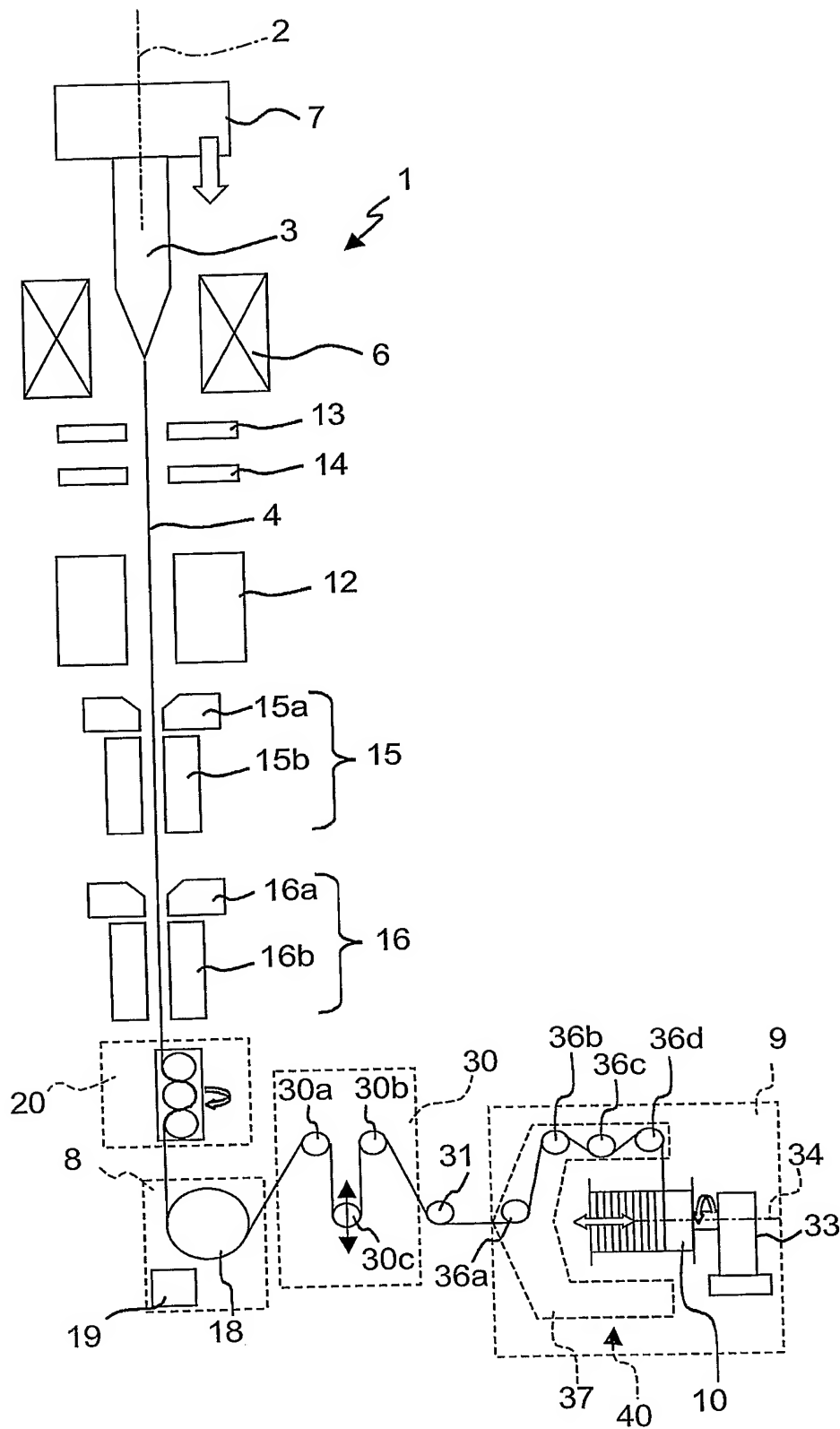
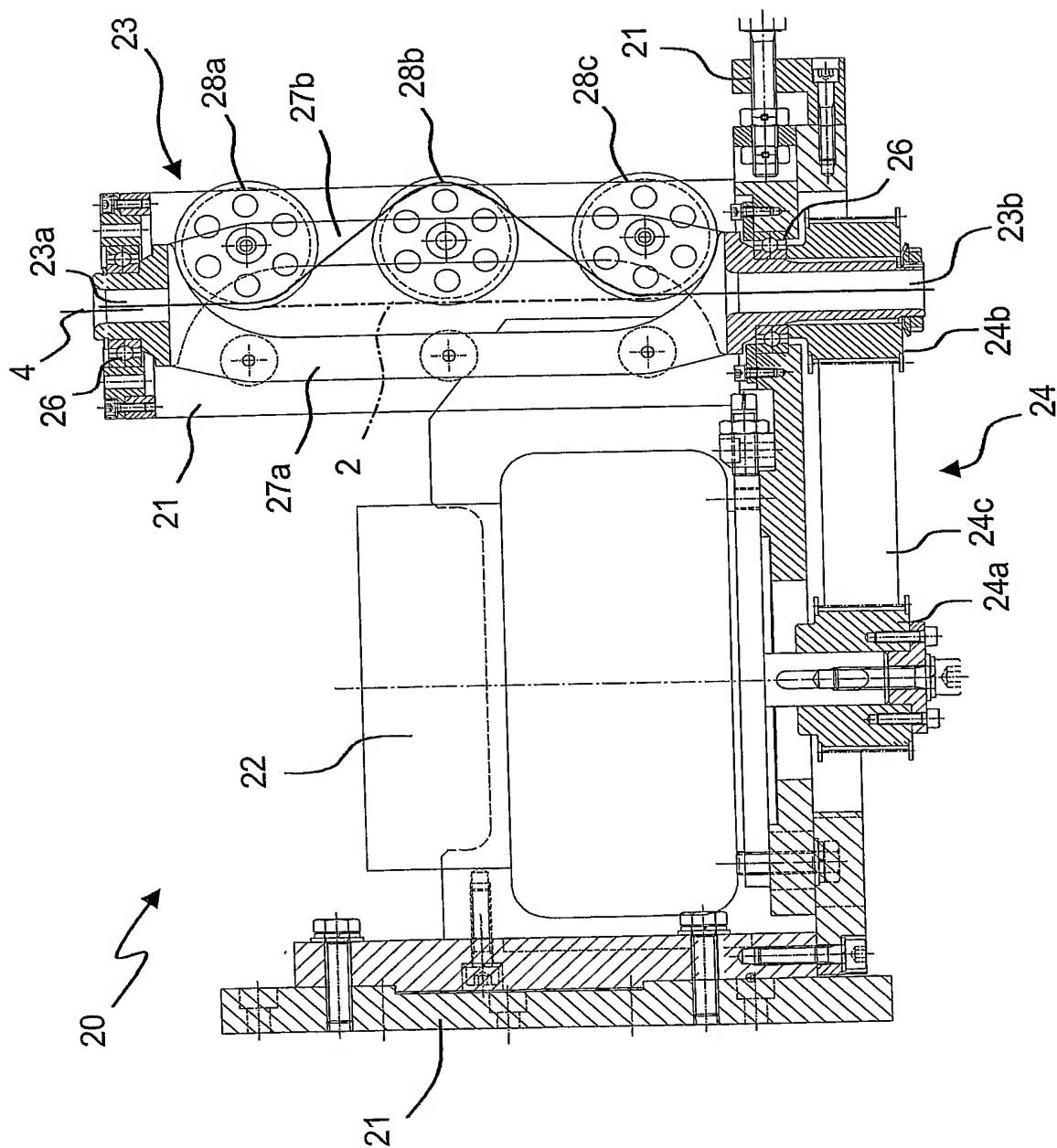


FIG. 7

FIG. 8



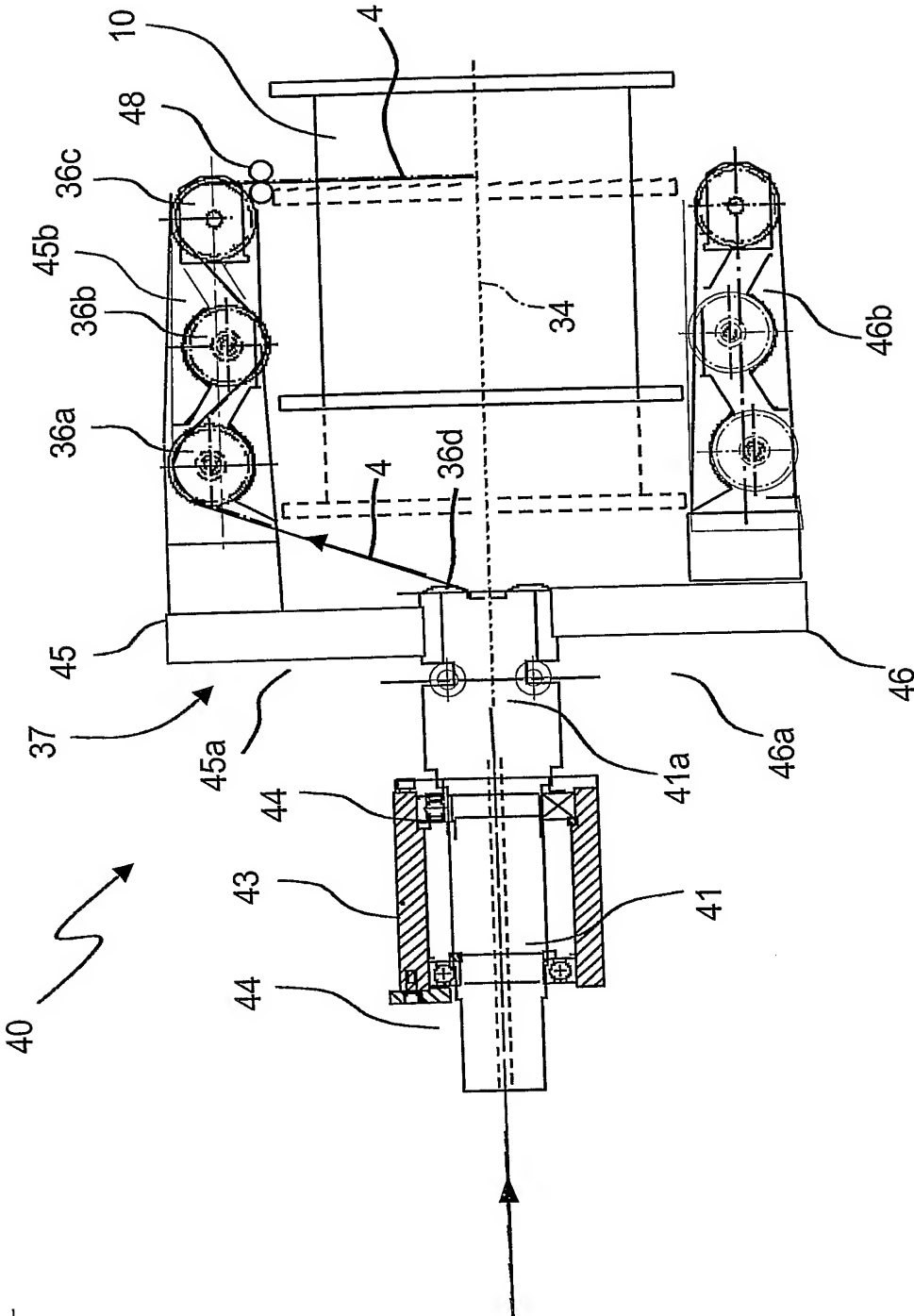


FIG. 9



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FIG. 11

10/11

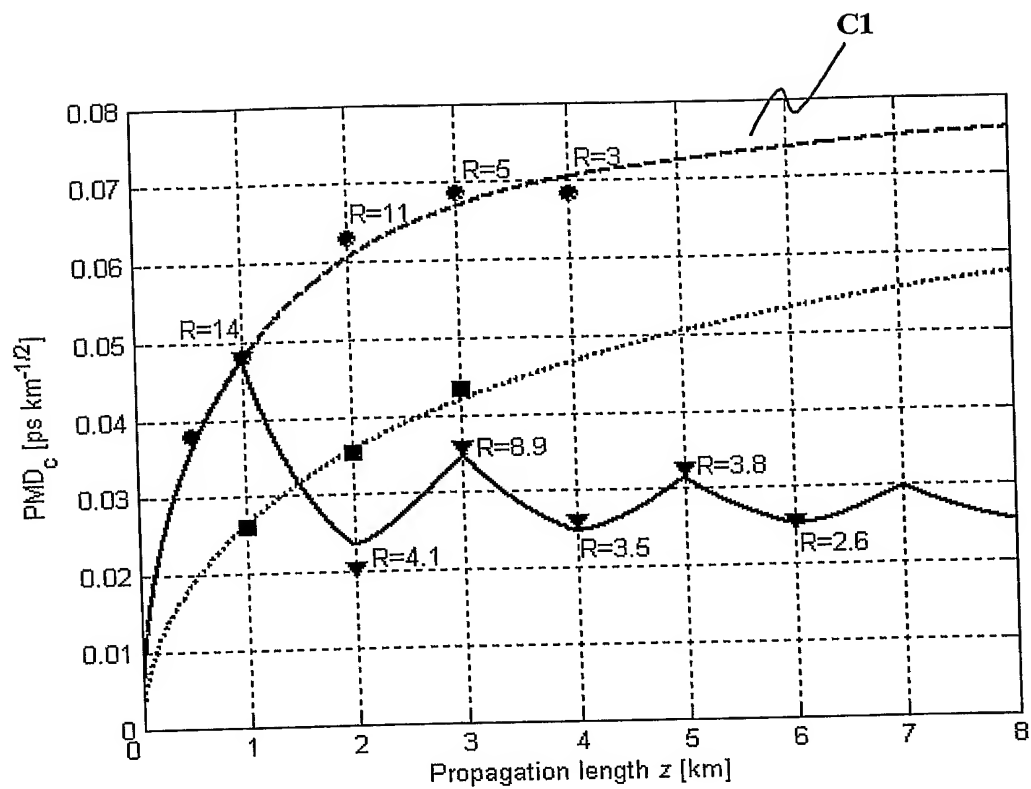


FIG. 12

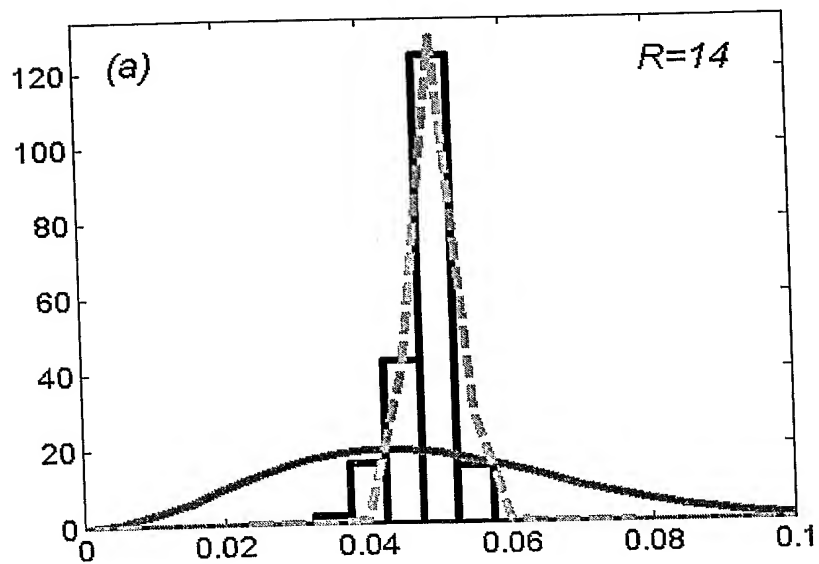


FIG. 13A

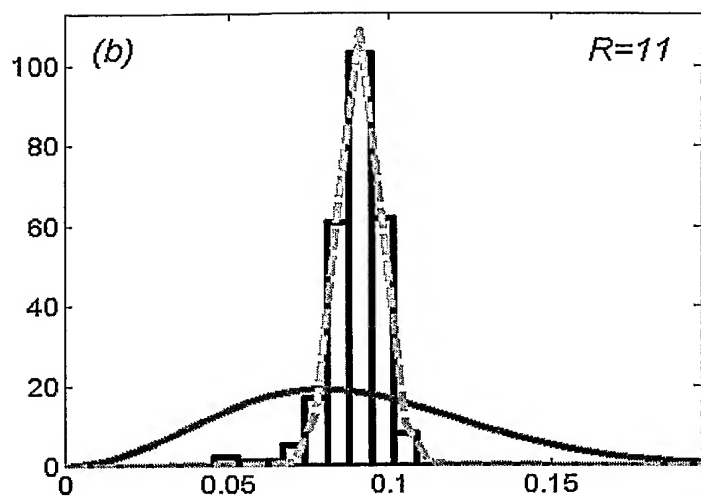


FIG. 13B

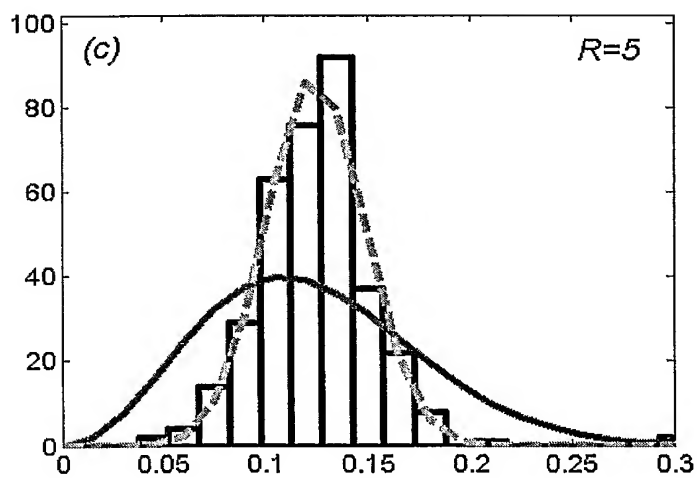


FIG. 13C

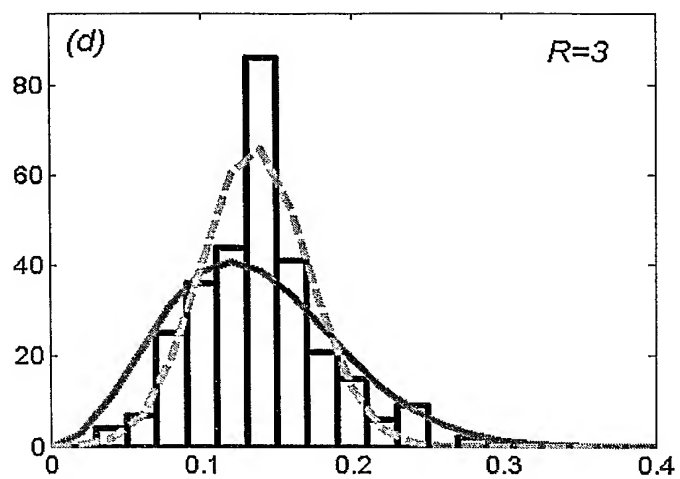


FIG. 13D